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The Anatomic Accuracy of Lateral Temporomandibular Joint Images from Axially Corrected Multidirectional Tomography and Three Panoramic Radiography Units: A Comparative Dry Skull Study

by

Dr. Farah A. Mawani

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science in Orthodontics

Department of Dentistry

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Date: July 18/03

Abstract

The purpose of this study was to evaluate the anatomic accuracy of lateral TMJ radiographs from axially corrected tomography and three panoramic radiography units and to evaluate the effect of varying horizontal and vertical head rotation.

The results revealed that there was a statistically significant amount of dimensional distortion on all lateral TMJ radiographs. The CommCAT images were the most dimensionally accurate, followed by the Orthophos DS, PM 2002 CC Proline, and the OP 100. A statistically significant difference in condylar shape was found between the lateral TMJ images from the tomography unit and each of the three panoramic radiography units. The PM 2000 CC Proline images demonstrated the smallest shape difference, followed by the OP 100 and the Orthophos DS. Variation in head position was found to have a statistically significant effect on the distortion indexes and the condylar shape for all three panoramic radiography units.

It appears that lateral TMJ images should be used with the understanding of the potential for image distortion in panoramic radiography, particularly since the degree and type of distortion cannot be defined or quantified in a clinical setting.

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Chapter One

Introduction
And
Literature Review

1.1 Literature Review

1.1.1 Introduction

Examination of the temporomandibular joint (TMJ) is an important aspect of diagnosis and treatment planning in orthodontics and dentofacial orthopedics, since TMJ disorders are the most common cause of chronic orofacial pain.[1] Population studies have estimated that 28% to 86% of adults experience occasional TMJ symptoms and 5% of these adults have symptoms severe enough to warrant seeking treatment.[2]

Radiographic imaging of the TMJ is indicated when patient history and clinical examination suggest the presence of a recent or progressive pathologic joint condition such as trauma, significant dysfunction or alteration in range of motion, sensory or motor alterations, or significant changes in occlusion (anterior or posterior open bites, mandibular shift).[3] The ideal imaging modality should provide the desired diagnostic information, while minimizing patient cost and radiation exposure. If there is a choice between imaging modalities that are expected to equally influence management of a patient, then the least expensive in terms of cost and radiation dose should be selected. [5, 4]

The TMJ is technically one of the most difficult areas of the body to image successfully because of multiple adjacent osseous structures.[1, 6] Currently, there are a variety of imaging modalities available for the TMJ that provide both conventional (analog) and digital images. Selecting an appropriate imaging modality requires knowledge of the type of diagnostic information required. This information may include cortical bone integrity, disk position, disk integrity, joint dynamics, and condylar position. In broad terms, plain film radiography, panoramic radiography, conventional tomography and computed tomography provide information about osseous structures,

while arthrography and MRI provide information about soft tissues. Because of the variety of imaging modalities available, it is important to understand the strengths and limitations of each technique. Inadequate radiographic imaging can occur for several reasons:

(1) Lack of clearly defined imaging objectives

(2) Poor knowledge of the imaging modalities available to achieve the defined objectives

(3) Imaging without appropriate image interpretation

(4) Imaging when the potential for obtaining diagnostic information is low.[4]

In 1997, the American Academy of Oral and Maxillofacial Radiology published a position paper to help general practitioners and specialists in selecting appropriate imaging modalities. This paper outlines imaging protocols when evaluating patients with a wide variety of temporomandibular joint related signs and symptoms.[5]

1.1.2 Digital Imaging

Radiographic images can be produced by a conventional (analog) process or by a more modern digital process. A conventional image is created by the interaction of ionizing radiation and x-ray film, while a digital image is created by converting digital information into a computerized image.[4, 7]

In recent years, digital panoramic and cephalometric imaging has become more prevalent in dental offices because of the many advantages offered by this system.[8] These include:

(1) Elimination of a darkroom and automatic processing equipment

(2) No chemical processing or chemical wastes

(3) Elimination of x-ray film

(4) Reduced radiation dose to the patient

(5) Lower cost per image

(6) Instant viewing of the image

(7) Ability to enhance the image

(8) Remote electronic consultation.

In most types of digital radiography, the x-ray beam or electromagnetic energy is converted into an electrical charge by an x-ray sensor. There are several types of sensors available, however the charged-coupled device (CCD) is used in dental radiography. Each CCD chip contains many photosensors and the charge on each photosensor is recorded as a voltage change. A computer with a digitizer samples the voltage values and converts them into an element array (pixels).[7] In digital panoramic radiography, CCD sensors are stacked to form a grid as tall as a standard panoramic film and several pixels wide. The CCD array is then moved around the patient in conjunction with the tube head to acquire the panoramic image one vertical line at a time.[8]

Spatial resolution and gray scale resolution are the two most important characteristics of a digital image and both should be considered when purchasing a digital imaging system. Spatial resolution is measured in terms of line pairs. A line pair (lp) refers to the largest number of paired lines visible in a 1mm space. Currently, the resolution for a panoramic image is 6 to 9 lp/mm. This means that the separation between six and nine individual lines can be seen in a 1mm space on a panoramic image. Spatial resolution is determined by both the number of pixels and the size of each pixel. The more pixels in an image and the smaller the size of each pixel, the greater the resolution.

Older sensors had pixels that were 70μ, while modern sensors have pixels as small as 25μ. [8] Grey scale resolution refers to the total number of shades of gray visible in an image. A standard 8-bit image can store up to 256 shades of gray, however most people can only see 16 to 25 shades. Higher gray scale resolutions are desirable because they are useful for enhancing images by suppressing unnecessary information.[8] For example, the Orthophos DS (Sirona Dental Systems) is a contemporary digital panoramic radiography unit with a physical pixel size of 45μ, a theoretical spatial resolution of 5.6lp/mm, and a gray scale resolution of 256 shades of gray.

1.1.3 Normal Anatomy of the TMJ

The osseous structures of the TMJ consist of the mandibular condyle and the mandibular (glenoid) fossa. The condyle is an ellipsoid structure connected to the ramus of the mandible by the condylar neck. The mediolateral axis of the condyle is longer than the anteroposterior axis. The average mediolateral length is 20mm while the anteroposterior length is 10mm.[1, 9] The angulation of the long axis of the condyle varies in both the horizontal and vertical planes. In the horizontal plane, the condyle is angulated towards the foramen magnum. The angle formed by the long axis of the condyle and the intermeatal line ranges from 11 to 35 degrees.[10] Variability of the condylar angulation in the vertical plane is considerably greater than the horizontal plane. In the vertical plane, the angle formed by the long axis of the condyle and the intermeatal line ranges from –45 to 35 degrees.[10] The mandibular fossa is composed of the articular fossa and articular eminence of the temporal bone. There is considerable individual variation in the height of the articular fossa.[1]

The articular disk (meniscus) is located between the condylar head and the articular fossa, dividing the joint into upper and lower compartments. Each compartment is lined with a synovial membrane and is filled with synovial fluid. The articular disk is a biconcave structure composed of fibrous connective tissue. The central zone of the disk is the thinnest (1.5mm) while the posterior band is the thickest (3mm). The posterior band is attached to a band of fibroelastic tissue termed the posterior ligament (also called the retrodiscal attachment or bilaminar zone). The disk plays an important role in the function of the temporomandibular joint. As the jaw opens, the bilaminar zone stretches, allowing the disk to move anteriorly with the condylar head. The disk therefore remains between the surfaces of the condylar head and the articular eminence. As the disk moves forward, tension is produced in the tissues of the bilaminar zone. This tension is thought to be responsible for the movement of the disk posteriorly as the jaw closes.[1]

Displacement of the articular disk is the most common disorder seen in patients with TMJ pain and dysfunction. Recently, disk displacement was found in 82% of 243 consecutive patients referred for bilateral magnetic resonance imaging.[11] The articular disk can be displaced in all directions, however anterolateral and anterior displacements are among the most common.[11] Only with magnetic resonance imaging (MRI) is it possible to determine the precise position of the disk and its posterior ligament in relation to the condyle.[1]

1.1.4 Plain Film Radiography

Plain film radiography is an imaging technique that uses the stationary x-ray source and film of standard dental x-ray units. Plain films depict only the osseous

structures of the TMJ. The major limitation of this technique is the superimposition of adjacent anatomic structures on portions of the TMJ. The most useful plain radiographs are the transcranial, the transmaxillary, and the submentovertex views (SMV).[5]

In the transcranial view, the x-ray film cassette is positioned on the side of interest, parallel to the sagittal plane, while the x-ray tube is positioned on the contralateral side of the patient's head. The angulation of the x-ray beam in the vertical plane limits the amount of superimposition of cranial base structures on the TMJ, while the angulation of the horizontal plane parallels the long axis of the condyle. The transcranial view represents only the lateral third of the TMJ in profile. The central and medial aspects of the joint are projected inferiorly onto the condylar neck because of the vertical angulation of the x-ray beam.[1, 12]

The transmaxillary view (also called transorbital or infraorbital) provides a frontal image of the TMJ by directing the x-ray beam perpendicular to the long axis of the condyle. In this technique, the film cassette is positioned behind the patient's head while the x-ray tube is placed in front. The image is taken with the mandible in a protruded position to allow the condyle to translate out of the fossa and onto the crest of the articular eminence.[1, 12] This view compliments the transcranial view and together they provide a three-dimensional evaluation of the joint for obvious fractures, neoplasms, anomalies and severe degenerative joint disease.[5]

The SMV view in TMJ imaging is used mainly to determine the position and orientation of the condyles in the horizontal plane. In this technique, the patient's head is extended backward as far as possible. The film is placed at the vertex of the skull and x-ray tube is placed at the chin. The x-ray beam is directed through the chin, parallel to the

posterior border of the ascending ramus.[1] The SMV can supplement the transcranial view to reveal condylar displacement and rotation associated with trauma or orthognathic surgery.[5]

1.1.5 Tomography

Tomography is one of the most widely used techniques to examine the osseous components of the TMJ. The main advantage of tomography over panoramic radiography is that it blurs out shadows of superimposed anatomical structures which obscure information pertaining to the TMJ. The tomographic image is generated by rotating the x-ray beam source and the film cassette in opposite directions (Figure 1.1). Structures near the center of rotation, called the tomographic plane, experience limited beam movement and appear focused, while all objects outside the focal plane experience blurring.[12] Tomography is not a method of improving sharpness of the radiographic image, but a process of controlled blurring of the structures that lie outside of the tomographic plane.[8]

X-ray tube motion in tomography can be classified into 5 main categories (Figure 1.2). Linear tomography has the least complex movement, in which the x-ray tube and the film move in one direction. Hypocycloidal tomography has the most complex tube motion and is often described as a cloverleaf. Complex motion tomography is preferred over linear tomography because it provides more effective blurring of structures outside the focal plane.[8]

Cross-sections of the TMJ can be made in two orientations with respect to the mediolateral long axis of the condyle. In the lateral view, the cross-section is perpendicular to the mediolateral long axis of the condyle, while in the frontal view the

cross-section is parallel to the mediolateral long axis of the condyle. In the axially corrected technique, the horizontal condylar axis angulation is first calculated on a submentovertex film (Figure 1.3). This individualized technique allows precise positioning of the x-ray beam relative to the anatomy of the condyle and produces the most reliable morphometric and morphologic information about the osseous components of the TMJ.[1, 13]

On a tomographic image, the disk and posterior ligament are referred to as the *joint space*.[1, 14] The joint space is a radiolucent area interposed between the osseous components of the condyle and mandibular fossa. A comparison of radiographic dimensions of the joint space is often used to determine the position of the condyle within the fossa. A number of imaging modalities have been evaluated for their ability to demonstrate positional changes of the condyle, however tomography appears to be the most accurate technique.[15] Condylar position can be characterized as anteropositioned, concentric, or retropositioned. The condyle is concentrically positioned if the anterior and posterior joint spaces are similar in width. Approximately one half to two thirds of asymptomatic subjects have concentrically positioned condyles.[16] However, condylar position is highly variable in both asymptomatic and symptomatic populations, therefore it remains unclear whether condylar position is a diagnostic sign of TMJ disorders.[17-19] As a result, "A diagnosis of dysfunction cannot be based solely on radiographic observation of nonconcentric condyle-fossa relationships."[16]

Many of these studies on condylar position have not considered the joint space in three dimensions. Hatcher et al. found that the width of the joint space in the sagittal plane varied from the medial to the lateral regions in 36% of all joints examined.[20]

Therefore, the classification of condylar position from joint space analysis may not be accurate unless the joint is represented in three dimensions. If joint space measurements are to be compared on serial radiographs, then skull position and radiographic projection should be identical.

A complete tomographic examination typically includes three closed lateral images and an open lateral image (Figure 1.4). The lateral tomographic images provide the best view of the cortical outlines of the mandibular condyle and fossa, as well as the position of the condyle within the fossa and its range of translatory motion.[1] However, with lateral tomography the medial, laterosuperior and mediosuperior surfaces of the condyle are more difficult to image than the central two thirds of the condyle, therefore axially corrected frontal images are recommended for viewing these surfaces.[13]

The ideal tomographic image is obtained when the patient is standing or seated in an upright posture, with the head stabilized by a cephalostat.[13] An upright posture is recommended instead of a supine posture because the spatial relationship of the structures within the TMJ may change with gravity. These specific features are available on the CommCAT (Imaging Sciences International Inc.). With this computer controlled tomography unit, one can select the desired orientation, thickness, and tube motion for imaging in any area of the maxillofacial region.[13] The versatility of this technique makes tomography highly desirable, although it is limited by its two-dimensional nature and by its inability to visualize soft tissues of the TMJ. Furthermore, the size and cost of these units preclude most practitioners from purchasing them. If tomographic images are desired, patients must be referred to diagnostic imaging centers.

1.1.6 Computed tomography (CT)

Computed tomography is an imaging technique that provides thin sections of the TMJ in several planes. It has a unique advantage over other conventional tomography since it has the ability to image both hard and soft tissues. In the area of the TMJ, it is most often utilized to image hard tissues, since the soft tissue articular disc in normal position is often lost in the background of the adjacent, high contrast condyle and fossa.[12, 13]

Current CT units consist of an x-ray tube that is mounted on a rotating gantry. The x-ray beam activity is recorded on an array of sensors positioned on the opposite side of the rotating gantry. The data is collected as a three dimensional matrix of small volumes or voxels, each assigned a value corresponding to the density of the tissue. The data can be reformatted to produce tomographic like sections.[12] Because multiple sections are made, it is possible to produce three-dimensional images reconstructed from the CT data.[1]

CT may be preferred over complex motion tomography for evaluating the osseous structures of the TMJ because of its three-dimensional imaging capabilities, however CT is more costly and has a relatively high radiation dose.[5] In a study of autopsy specimens, Tanimoto et al. found that complex motion tomography is superior to CT in the diagnosis of single structural osseous changes, but comparable for comprehensive diagnosis of degenerative joint disease.[21] Brooks et al. suggested that CT of the TMJ should be reserved only for evaluation of foreign body giant cell reaction to Silastic (Dow Corning, Midland, Michigan) or Teflon-Proplast (Teflon: Dupont, Wilmington, Delaware) implants, suspected tumors, ankylosis and complex facial fractures. [5]

1.1.7 Arthrography

Arthrography is a technique that images the soft tissues of the TMJ. Soft tissue imaging of the TMJ is used to:

(1) Examine the position of the articular disk throughout the range of mandibular movement

(2) Determine the presence of adhesions

(3) Determine the presence of perforations between the superior and inferior joint compartments

(4) Detect joint effusions (excessive fluid inside the capsule).[13]

Arthrography involves injecting a contrast medium (iodine and/or air) into one or both joint spaces. On the radiographic image, the disk appears as a radiolucent mass against the background of a radiopaque contrast medium. The location, shape, and movement of the disk can be interpreted by observing the flow of the contrast medium during mandibular movement. A fluoroscope allows for real time visualization of the disk, whereas static images can be produced using plain radiography or tomography (arthrotomography).[1]

In the past, arthrography was considered the method of choice for demonstrating TMJ internal derangements and was crucial to the understanding of soft tissue joint dynamics. [1] Arthrography is now considered a relatively high-risk procedure due to the radiation exposure, percutaneous injection into the TMJ, and potential for allergic reaction to the contrast media.[7] Less invasive techniques such as MRI have to a large extent replaced it.

1.1.8 Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging is a revolutionary imaging technique that uses a magnetic field and radiofrequency pulses instead of ionizing radiation. It is the preferred technique for imaging the soft tissues because diagnostic value is high while risk to the patient is low.[5, 7, 12, 13] Currently, MRI is the most accurate imaging modality for identification of disk position in the TMJ.[22]

The method for generating an MR image is unlike any imaging technique that uses ionizing radiation. It is based on the presence of hydrogen ions in the body, which are found in abundance in water-containing tissues and in hydrocarbons such as fat. Each hydrogen ion has a nucleus with one proton. Each proton has a charge and a movement (spin) that combine to form a magnetic moment. The magnetic moment of a proton, which is normally randomly oriented, aligns when exposed to a magnetic field produced by the superconducting magnet. Computer-controlled radiofrequency pulses are sent by a transmitter and are absorbed by the protons. The removal of the radiofrequency pulses allows the excited protons to return to a lower energy level (relax). The released energy generates a signal that can be received by a surface coil and is stored as raw data on a computer. This data can then be used to generate either two-dimensional sections in almost any spatial plane or three-dimensional images. The strength of the signal is proportional to the number of protons (water) in a given area and is the determinant of tissue contrast on an MR image.[12, 13]

Computed tomography, arthrography, and magnetic resonance imaging are the preferred techniques for evaluating osseous structures, joint dynamics, and disk position

in the TMJ.[23] These techniques are costly and are not widely used by dental practitioners. In the case of arthrography and CT, they have the additional risk of producing relatively high doses of radiation.[5]

1.1.9 Panoramic Radiography

Panoramic radiography (also called pantomography, orthopantomography, or panoramic rotational radiography) is a widely used imaging technique in dentistry.[1] The two main advantages of panoramic radiography over a series of intraoral radiographs are: (1) it produces a single image of the facial structures, including both maxillary and mandibular arches and their supporting structures, and (2) the patient radiation dose is low, especially with the use of rare earth intensifying screens. The radiation dose for a panoramic radiograph is equivalent to approximately three or four periapicals films.[1, 6, 24]

The principle of panoramic radiography is similar to tomography in that the x-ray beam source and film cassette carrier are moving in opposite directions. With panoramic radiography, the film cassette also moves within the cassette carrier in the same direction as the x-ray beam. The movement of the film allows a different part of the film to be exposed to the x-ray beam at any one instant, so that by the end of the cycle the entire film has been exposed.[6] In panoramic radiography, a vertical narrow x-ray beam is used instead of the larger circular or rectangular x-ray beams used in conventional intraoral radiography. The x-ray beam has a slight negative angulation ranging from 4 to 7 degrees, allowing it to pass underneath the base of the skull (Figure 1.5). Many panoramic radiography machines have x-ray beams with a continuously moving rotation center that follows a defined path (Figure 1.6). The form of the defined curved path

dictates the direction of the x-ray beam in relation to the objects being imaged.[8] The optimal path should direct the x-ray beam as close to perpendicular as possible to all parts of the object. In actual practice, the beam is rarely 90 degrees. The maximum beam angle occurs in the premolar region at 110 to 120 degrees. This angle decreases to between 40 and 70 degrees in the area of the ascending ramus and the TMJ.[25]

Unlike axially corrected tomography of the TMJ, the direction of the x-ray beam in panoramic radiography is not parallel to the long axis of the condyle. As a result, the outline of the condyle and mandibular fossa on a panoramic image is an oblique section of the TMJ.[26,27] An understanding of how the TMJ is depicted on a panoramic radiograph is essential when utilizing this technique as a diagnostic tool. The angulation of the x-ray beam in the TMJ area varies among different manufacturers and is dependent upon the position of the patient's head in the apparatus. In general, the lateral condylar pole is visualized as the anterior border of the condyle, the posterior pole is visualized correctly as the posterior border of the condyle, and the medial pole is superimposed over the center of the condyle near the posterior condylar border. In some instances, the medial pole may be superimposed over the posterior border of the condyle.[26] Because of this oblique projection, interpretation of osseous changes can only be made on the lateral pole of the condyle.[26] The mandibular fossa is less evident than the condyle on the panoramic radiograph, since superimposition of the base of the skull and the zygomatic arch does not allow for adequate visualization of the entire structure.[27]

However complex the relationship of the various structures appear to be, the panoramic radiograph may give a relatively reliable impression about the angulation of the condyle. The wider the condyle appears on the image, the more angulated to the

posterior it usually is. Hollender uses this information from the panoramic radiograph to select a standardized condylar axis angulation for lateral or frontal tomography.[26]

To improve the quality of the TMJ image on panoramic radiographs, Chilvarquer et al. proposed a new patient positioning technique using the Panoral panoramic machine (J. Morita Corporation, Kyoto, Japan). In this technique, a submentovertex image must be taken to determine the correct horizontal condylar axis angulation. The patient is then repositioned to place the TMJ within the sharply depicted plane of the focal trough, so that the x-ray beam is aligned with the long axis of the condyle instead of passing obliquely through the condyle (Figure 1.7) Following a subjective assessment of the panoramic radiographs, the authors suggested that this individualized patient positioning could minimize distortion and improve image sharpness.[28]

One major limiting factor in the clinical use of panoramic radiography is the inability to confirm whether the dimensions of the structures shown on the radiographic images correspond to the anatomic truth.[29] Dimensional accuracy is determined by image magnification in the vertical and horizontal planes. The position of an object between the x-ray source and the film is responsible for the magnification seen on a radiographic image. In the central plane of the focal trough the image is free of distortion, which means that the magnification is the same in both vertical and horizontal dimensions (Figure 1.8). Objects outside this plane will appear distorted and blurred on the image because of the difference between the velocity of the film and the velocity of the projection of the object on the film. [30, 31]

Three types of distortion that may occur on a panoramic image have been described in the literature. Distortion of object morphology or shape is referred to as *form*

distortion; distortion of the size of an object is referred to as *area distortion*; distortion of the angulation between objects is referred to as *angle distortion*.[32, 33] To minimize distortion on a panoramic radiograph, the patient should be positioned such that the dental arches including the TMJ are located within the central plane of the focal trough. This is achieved by aligning the midsagittal plane with the center of the focal trough, aligning the Frankfort horizontal plane parallel to the floor, and by having the patient place the incisal edges of the maxillary and mandibular incisors into a notched positioned device (bite block). [1] Schiff et al. investigated common positioning and technical errors from a sample of randomly selected panoramic radiographs (Figure 1.9). Of the 1000 radiographs examined, only 20% were error free. Positioning errors were found more frequently than technical errors; therefore the authors emphasized the need for adequate training in patient positioning.[34]

The size and shape of the focal trough varies between manufacturers, some focusing on the TMJ more than others.[12] The focal trough is designed to match a generic mandibular form, which is elliptical and horseshoe shaped. The best panoramic radiographs are obtained when the patient's anatomy approximates this generic mandibular form.[7] Some manufacturers allow for minor adjustments of the focal trough to better match the patient's unique mandibular anatomy. For example, the PM 2002 CC Proline (Planmeca) provides nine different combinations of image layer sizes and shapes to choose from. The magnification factors also vary between manufacturers because of the differences in x-ray beam projection geometries.[35, 36] While data on the average magnification along the central plane of the focal trough is available, the continuous variation of the magnification factors in the horizontal and vertical plane have not been

published.[25] Furthermore, the magnification factor can vary between units made by the same manufacturer. It is therefore essential to use the same panoramic radiography unit in longitudinal studies.[31]

There have been numerous experimental studies that have tested the dimensional accuracy of panoramic radiographs. Dimensional measurements on panoramic radiographs cannot be made without mathematical correction by the magnification factor. Tronje et al. used a mathematical model to theoretically analyze the reliability of the reproduction of vertical measurements on panoramic images. This mathematical model was tested using an experimental model designed by the authors and attached to the Philips OrthOralix. They found that any measurement in the horizontal dimension on panoramic radiographs was unreliable. However, measurements of structures that are anatomically known to be close to vertical were reliable if the patient was positioned properly.[30, 37]

Catic et al. evaluated the precision of dimensional measurements in the mandible of a human dry skull using the Orthophos D3200 (Siemens).[29] Using metal markers as landmarks, the authors measured various vertical, horizontal and oblique distances on the mandible and compared them to the corresponding radiographic distances. Results revealed that the magnification indexes for the horizontal and oblique distances on one side of the mandible ranged from 0.97 – 1.07 and 1.09-1.12 respectively, which was significantly lower than the manufacturer's reported index (1.22). However, for horizontal distances that traversed the midline of the mandible, the magnification indexes were significantly higher, ranging from 1.45 to 1.85. The magnification indexes for the vertical distances were not significantly different from the manufacturers index with

values ranging from 1.13-1.23. The authors concluded that the dimensions of structures on the panoramic images were similar to the actual dimensions as long as the distances measured do not cross the midline of the mandible. As a result, they suggested that it is possible to use panoramic radiography for vertical, horizontal or oblique linear measurements as long as the distance is on one side of the mandible.[29] This statement was misleading since the vertical measurements had magnification indexes that were similar to the manufacturers reported index, therefore the distances would have to be mathematically corrected to be precise.

In a recent study, Scarfe et al. investigated the vertical and horizontal magnification factors and the distortion index for the OP 100 (Instrumentarium Imaging) using a reference object placed at various resolutions limits of the focal trough. The vertical magnification factor of each resolution limit within the focal trough showed a linear increase along the beam path from 1.24 to 1.37, while the horizontal magnification varied from 1.01 to 1.63. The horizontal and vertical magnifications were identical at the center of the trough (1.28) and essentially constant throughout the image. The distortion index, defined as the ratio of the vertical magnification factor to the horizontal magnification factor varied from 0.84 to 1.24.[38]

Habets et al. designed an experimental model to determine the accuracy of bilateral vertical measurements specifically in the TMJ region. They found that a 6% difference between the left and right images was inherent in panoramic radiography. On the basis of those results, they proposed a method for measuring condylar and rami heights, and suggested that a discrepancy of more than 6% between the corresponding right and left sides should be considered an asymmetry.[39] Using the same method for

measuring rami and condylar heights, Türp et al. did not find any correlation between 25 dry skulls and their images.[40]

Another limiting factor in the clinical use of panoramic radiography is the displacement of structures on the radiographic image. This is particularly important when evaluating condylar position. In a dry skull study, Ruf and Pancherz examined the accuracy of panoramic radiography in reproducing the anatomy of the TMJ at various head positions. Metal markers were placed on the medial, lateral and posterior poles of the condyle and on the lateral, central and medial third of the mandibular fossa. Ruf and Pancherz found that the relationship of the condyle and fossa on the panoramic radiographs did not correspond to the true anatomic relationship. With increasing skull retroclination, the condyle was projected more inferiorly relative to the fossa, while skull anteclination projected the condyle more superiorly. Furthermore, they found that changes in head position could affect the morphology of the condyle and fossa. Visual inspection of the panoramic radiographs revealed anterior condylar flattening, simulation of osteophytes, and left/right condylar asymmetry.[27] Based on the results of this study, Ruf and Pancherz questioned the reliability of panoramic radiography for diagnosis of TMJ disorders because of the effects of distortion and displacement on the radiographic image.

Panoramic radiography has been studied for over 50 years, since its introduction in 1948 by Yrjo Paatero.[41, 42] Although this imaging modality is widely used by orthodontists, the use of panoramic radiography for temporomandibular joint imaging remains controversial. Panoramic radiography may not be capable of accurately and reliably representing the size, shape and relationship of the TMJ anatomy because of the

effects of area distortion, form distortion and displacement on the radiographic image. However, many authors continue to advocate the use of this imaging technique as an initial screening tool, with the understanding that it is not considered suitable for detailed visualization of osseous structures.[5, 7, 12, 13, 26]

Based on the information provided by the panoramic radiograph, decisions can be made regarding further radiographic examination. In view of the increasing costs of health care and the staggering costs of using modern imaging modalities, such an approach is desirable. If identification of gross osseous changes is the goal, than panoramic radiography may be the only TMJ imaging necessary.[5]

In recent years, there have been many technological advances in panoramic radiography. Newer generation panoramic radiography units such as the Orthophos CD (Sirona, Germany), the PM 2002 CC Proline (Planmeca, Finland), and the OP100 (Instrumentarium, Finland) have specialized programs that may improve the accuracy of TMJ imaging. Conventional panoramic programs provide an oblique section of the TMJ, however these specialized TMJ programs are designed to provide an arbitrary correction for horizontal condylar axis angulation based on population norms.[43]

The Orthophos CD (Sirona, Germany) has sixteen panoramic programs of which six are TMJ-specific. These six programs include right and left lateral views, right and left frontal views, right and left lateral views with closed and open mouth positions on one film, right and left frontal views with closed and open mouth positions on one film, lateral multi-layer views, and frontal multi-layer views (Figure 1.10). The PM 2002 CC Proline (Planmeca, Finland) has two TMJ-specific programs which include: right and left lateral views with closed and open mouth positions on one film and right and left frontal

views. One unique feature of the PM 2002 CC Proline is the optional *True Profile Program*, which provides axially corrected TMJ images. The required projection angle is determined using a submento-vertex radiograph and is adjusted without rotating the patient's head. The OP100 (Instrumentarium, Finland) has four TMJ-specific programs that include right and left lateral views, right and left frontal views, right and left lateral views with closed and open mouth positions on one film, and right and left frontal views with closed and open mouth positions on one film. Similar to the PM 2002 CC Proline, the OP 100 has an optional *Ortho TMJ* program that allows the clinician to set the x-ray beam angle equal to the horizontal condylar axis angulation.

The goal of using any new technique is to accurately represent the *anatomic truth* of the structure being imaged. However, there are very few studies in the literature that have examined the accuracy of TMJ-specific panoramic programs. Tyndall et al. compared the diagnostic accuracy of TMJ panoramic radiography with axially corrected multidirectional tomography.[44] In this study, dentinal chips of various sizes were placed on the condyle of a dry human skull to simulate arthritic lesions. When biplanar (lateral and frontal) panoramic images were compared to lateral tomographic images, no statistically significant difference in lesion detection was found. Based on these results, the authors suggested that biplanar panoramic images could yield the same diagnostic information as lateral tomographic images. In a subsequent study, the authors determined that when biplanar tomography was used, lesion detection was significantly more reliable than biplanar panoramic radiography.[43] Although this initial study supports the use of multidirectional tomography over TMJ panoramic radiography, further research is required to determine the value of this imaging technique.

The purpose of this study was (1) to compare the true dimensions of the TMJ of a dry human skull to the radiographic dimensions on lateral TMJ radiographs from axially corrected tomography and three panoramic radiography units, (2) to compare the radiographic shape of the condyle between lateral TMJ images from axially corrected tomography and three panoramic radiography units, and (3) to evaluate the effect of varying horizontal and vertical head rotation on the radiographic dimensions of the TMJ and the shape of the condyle from each of three panoramic radiography units and to compare these findings to the ideal head position.

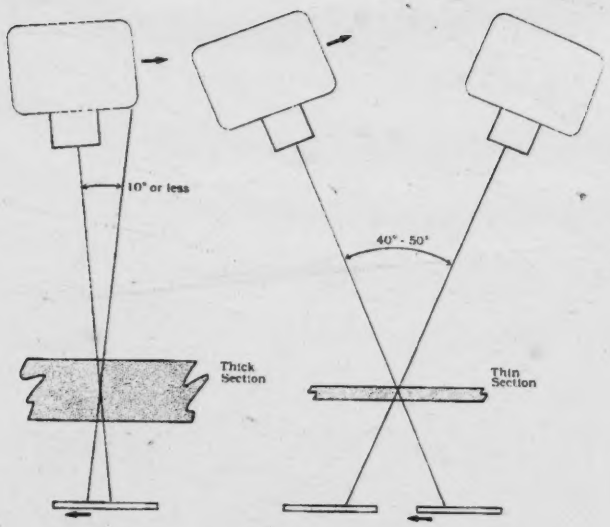

Figure 1.1 Image Generation in Tomography. The x-ray beam source moves in one direction, while the film cassette moves in the opposite direction. Note that the angles of exposure determine the thickness of the tomographic plane. (From Langland OE et al. 2002; 11: 277)

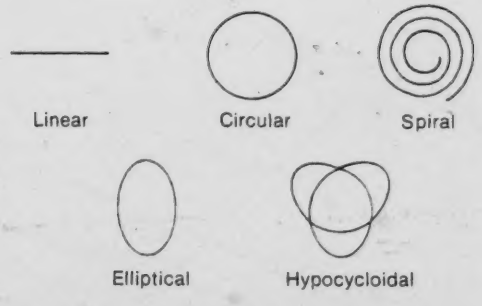

Figure 1.2 Types of X-ray Tube Motion in Tomography. Note that the types of tomography are listed in order of increasing tube-film movement complexity. The more complex the tube-film movement is, the greater the ability to blur adjacent anatomy. (From Goaz PW: White SC 1994; 13: 267)

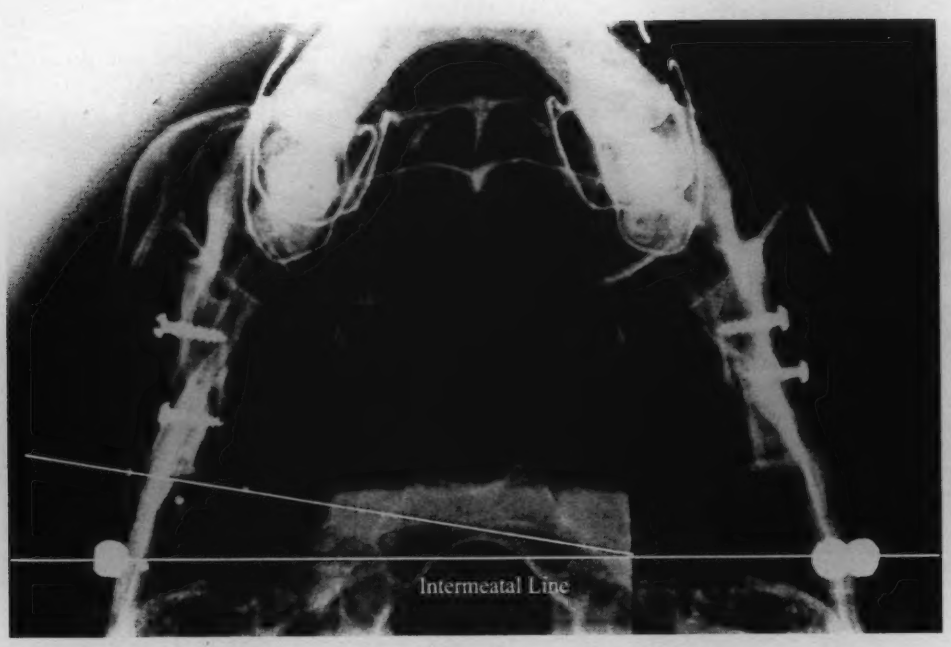

Figure 1.3 Submentovertex Projection for Horizontal Condylar Axis Angulation. The angle formed by the mediolateral long axis of the condyle and the intermeatal axis is used to calculate the horizontal condylar axis angulation in axially corrected tomography. Note that the intermeatal line is constructed by connecting the radiographic images of the cephalostat ear rods.

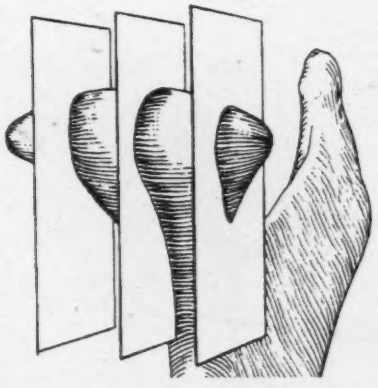

Figure 1.4 Lateral Tomographic Slices. Tomographic slices are made at 2-3mm intervals from the medial pole to the lateral pole. (From Langland OE et al. 2002; 11: 277)

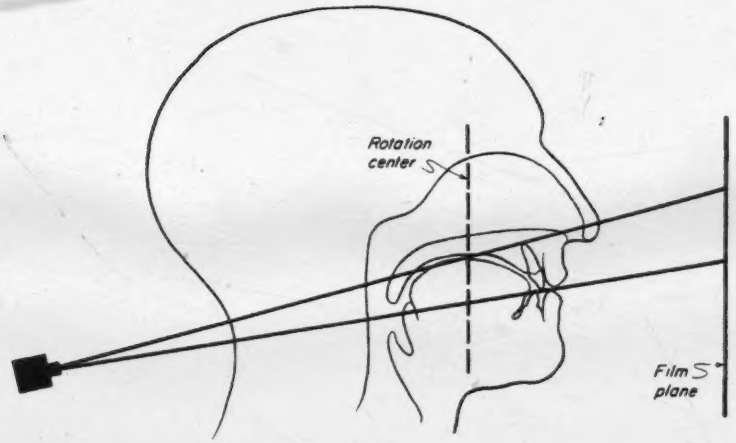

Figure 1.5 Projection of the X-ray Beam in the Vertical Plane in Panoramic Radiography. The x-ray beam has a slight negative angulation (4 to 7 degrees), allowing it to pass beneath the occipital portion of the skull. (From Langland OE et al. 2002; 9: 202)

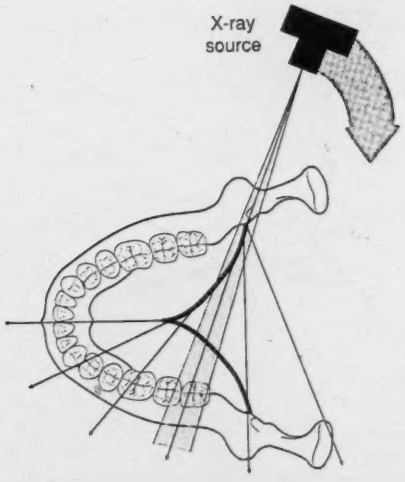

Figure 1.6 Rotation Centers in Panoramic Radiography. The dark line shows a continuously moving center of rotation. Note that the center of rotation is near the lingual surface of the right side of the mandible when the left TMJ is imaged. As the x-ray source moves behind the patient's neck, the rotation center moves anteriorly towards the sagittal plane and ends just lingual the mandibular symphysis. The arc is reversed as the opposite side of the patient is imaged. (From Goaz PW: White SC 1994; 12: 244)

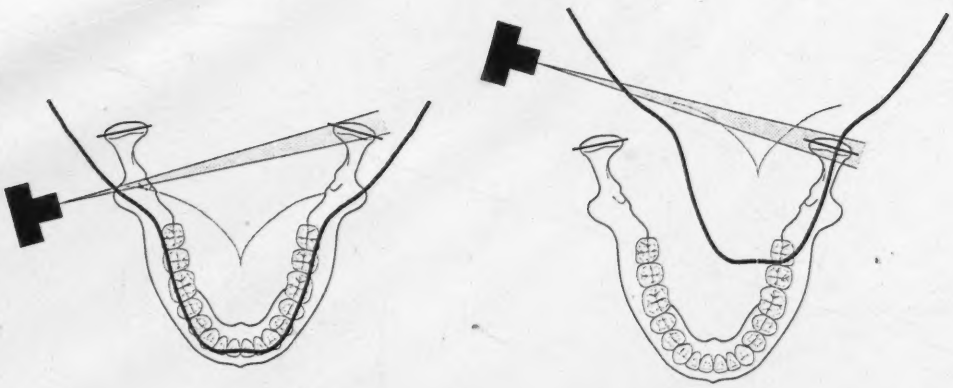

Figure 1.7 Head Positioning for Panoramic Imaging of the TMJ. In conventional panoramic radiography, the x-ray beam is directed at an oblique angle relative to horizontal axis of the condyle. When the patient's head is displaced forward and laterally towards the x-ray source, the x-ray beam can be directed parallel to the horizontal axis of the condyle. (From Goaz PW: White SC 1994; 12: 251)

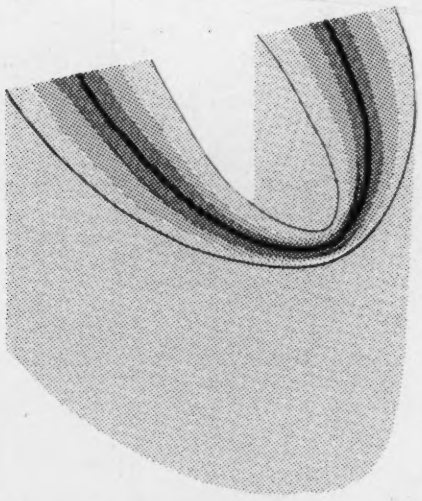

Figure 1.8 Focal Trough in Panoramic Radiography. The dark line in the middle of the focal trough represents the central plane. The further an anatomic structure is positioned relative to the central plane, the greater the amount of distortion and blurring on the radiographic image. (From Goaz PW: White SC 1994; 12: 245)

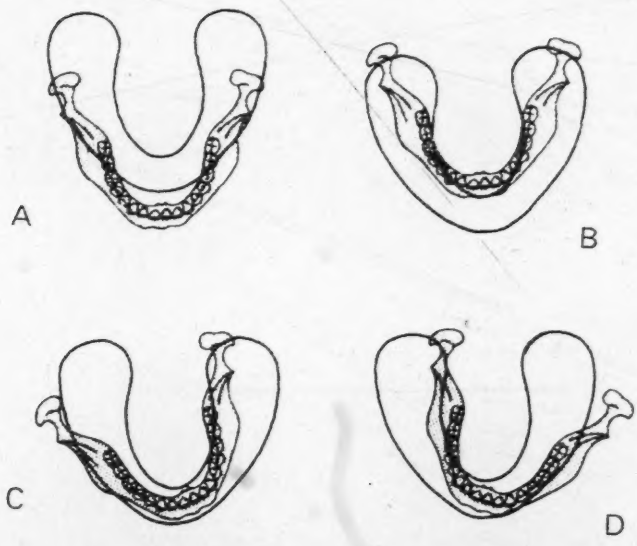

Figure 1.9 Common Positioning Errors in Panoramic Radiography. Diagrams show the position of the mandible in relation to the focal trough when the patient is not positioned correctly. **A** The patient is positioned too close to the film or the head is rotated upward, placing the mandible in front of the focal trough. **B** The patient is positioned too far away from the film or the head is rotated downward, placing the mandible behind the focal trough. **C** and **D** The patient is positioned asymmetrically with the head rotated to either the right or left. (From Whaites E 2002; 15: 1968)

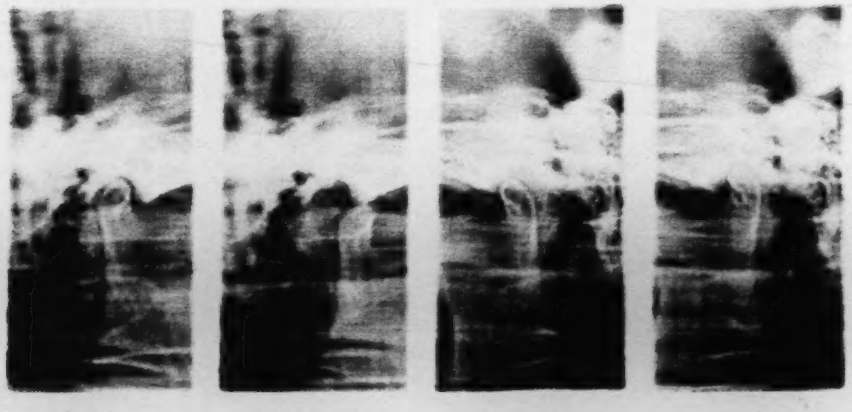

Figure 1.10 Lateral TMJ Panoramic radiographs: Open and Closed Positions. Panoramic radiograph demonstrating lateral views of the right and left TMJ in an open and closed position.

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1.3 Research Questions

Paper #1

1. Is there a difference between the calculated horizontal magnification indexes of lateral TMJ images from axially corrected tomography and three panoramic radiography units?

2. Is there a difference between the calculated vertical magnification indexes of lateral TMJ images from axially corrected tomography and three panoramic radiography units?

3. Is there a difference between the calculated joint space magnification indexes of lateral TMJ images from axially corrected tomography and three panoramic radiography units?

4. Is there distortion of the lateral TMJ images from axially corrected tomography and three panoramic radiography units and axially corrected tomographic images?

Paper #2

5. Is there a difference in the condylar shape between lateral TMJ images from axially corrected tomographic images and each of three panoramic radiography units?

Paper #3

6. Is there a difference in the distortion indexes between lateral TMJ images at ideal head position and varying horizontal head position (i.e. 5 to the right and 5 to the left) on lateral TMJ images from each of three panoramic radiography units?

7. Is there a difference in the distortion indexes between lateral TMJ images at ideal head position and varying vertical head position (i.e. 5 up and 5 down) from each of three panoramic radiography units?

8. Is there a difference in condylar shape between ideal head position and varying horizontal head position (i.e. 5 to the right and 5 to the left) on lateral TMJ images from each of three panoramic radiography units?

9. Is there a difference in condylar shape between ideal head position and varying vertical head position (i.e. 5 up and 5 down) on lateral TMJ images from each of three panoramic radiography units?

1.2 Null Hypotheses

Paper #1

1. There is no difference between the calculated horizontal magnification indexes of lateral TMJ images from axially corrected tomography and three panoramic radiography units.

2. There is no difference between the calculated vertical magnification indexes of lateral TMJ images from axially corrected tomography and three panoramic radiography units.

3. There is no difference between the calculated joint space magnification indexes of lateral TMJ images from axially corrected tomography and three panoramic radiography units.

4. There is no distortion of the lateral TMJ images from axially corrected tomography and three panoramic radiography units and axially corrected tomographic images.

Paper #2

5. There is no difference in the condylar shape between lateral TMJ images from axially corrected tomographic images and each of three panoramic radiography units.

6. There is no difference in the distortion indexes between lateral TMJ images at ideal head position and varying horizontal head position (i.e. 5 to the right and 5 to the left) on lateral TMJ images from each of three panoramic radiography units.

7. There is no difference in the distortion indexes between lateral TMJ images at ideal head position and varying vertical head position (i.e. 5 up and 5 down) from each of three panoramic radiography units.

8. There is no difference in condylar shape between ideal head position and varying horizontal head position (i.e. 5 to the right and 5 to the left) on lateral TMJ images from each of three panoramic radiography units.

9. There is no difference in condylar shape between ideal head position and varying vertical head position (i.e. 5 up and 5 down) on lateral TMJ images from each of three panoramic radiography units.

Chapter Two

Research Paper One

A Comparative Study of the Dimensional Accuracy of Lateral Temporomandibular Joint Images from Three Panoramic Radiography Units and Axially Corrected Multidirectional Tomography

2.1 Introduction:

Radiographic examination is an important aspect of the overall assessment of patients with temporomandibular joint (TMJ) pain and dysfunction. Currently, there are a variety of imaging modalities available that provide both conventional and digital images of the TMJ. The ideal imaging modality should provide the desired diagnostic information, while minimizing patient cost and radiation exposure.

Panoramic radiography is frequently used in the initial radiographic examination of the TMJ.[1-4] It is a cost effective technique that has a reasonably low patient radiation dose.[5] Based on the information obtained from the clinical examination and the panoramic radiograph, the need for further radiographic imaging can be determined by the practitioner. In view of the cost of using modern imaging modalities such as magnetic resonance imaging and the high radiation doses associated with arthrography and computed tomography, such an approach to patient management is desirable.

The major limiting factor in use of panoramic radiography for TMJ imaging is the effect of distortion on the radiographic image. In the central plane of the focal trough the image is free of distortion, which means that the magnification factor is identical in both the horizontal and vertical dimensions. Objects outside this plane will appear distorted and blurred.[6, 7] The second major limiting factor is geometry of the x-ray beam relative to the anatomy of the TMJ. The direction of the x-ray beam in panoramic radiography is not parallel to the long axis of the condyle, therefore the radiographic image is an oblique section of the TMJ.[8, 9] Many investigators have described these limitations in detail and a few have studied the diagnostic possibilities witj regard to TMJ changes. [6, 10-23]

Tomography is one of the most widely used techniques to examine the osseous

components of the TMJ.[24] The American Academy of Oral and Maxillofacial Radiology has recommended the use of conventional tomography because of the cost and the relatively high risk of radiation exposure associated with computed tomography.[3] The main advantage of tomography over panoramic radiography is that it blurs out shadows of superimposed anatomic structures which obscure information pertaining to the TMJ. In the axially corrected technique, the horizontal condylar axis angulation is calculated using a submentovertex film to allow precise positioning of the x-ray beam relative to the anatomy of the condyle. Axially corrected images provide the most reliable and accurate information about the osseous components of the TMJ.[4, 24]

In recent years, there have been many technological advances in panoramic radiography. Newer generation panoramic radiography units have specialized TMJ programs that are designed to provide an arbitrary correction for horizontal condylar axis angulation based on population norms.[25] Similar to tomography, many of these panoramic radiography units can provide both lateral and coronal views of the TMJ in the open and closed mouth positions.

The goal of using any new technique is to accurately represent the "anatomic truth" of the structure being imaged. However, there are very few studies in the literature that have examined the accuracy of TMJ-specific panoramic programs. Tyndall et al. compared the diagnostic accuracy of TMJ panoramic radiography with axially corrected multidirectional tomography.[26] In this study, dentinal chips of various sizes were placed on the condyle of a dry human skull to simulate arthritic lesions. When biplanar (lateral and frontal) panoramic images were compared to lateral tomographic images, no statistically significant difference in lesion detection was found. Based on these results,

the authors suggested that biplanar panoramic images could yield the same diagnostic information as lateral tomographic images. In a subsequent study, the authors determined that when biplanar tomography was used, lesion detection was significantly more reliable than biplanar panoramic radiography.[25] Although these initial studies support the use of multidirectional tomography over TMJ panoramic radiography, further research is required to determine the value of this imaging technique.

The purpose of this study was to compare the true dimensions of the TMJ from a dry human skull to the radiographic dimensions on lateral TMJ radiographs from axially corrected tomography and three panoramic radiography units.

2.2 Materials and Methods

2.2.1 Skull Testing Device Design

A dry human skull with an intact TMJ and a stable occlusion was selected. Radiopaque markers consisting of stainless steel balls approximately 1.58mm in diameter were used as reference points. These markers were fixed onto the surface of the right condyle following preparation with a #2 round bur. The location of the markers on the surfaces of the condyle and fossa are as follows (Figure 2.1):

1. Most superior point of the condyle (CS)
2. Three points along the anterior surface of the condyle (CA_1, CA_2, and CA_3)
3. Three points along the posterior surface of the condyle that correspond to CA_1, CA_2, and CA_3 (CP_1, CP_2, and CP_3)
4. Most superior point of the mandibular fossa (FS)

5. A point along the anterior surface of the mandibular fossa that corresponds to CA_1 (FA)
6. A point along the posterior surface of the mandibular fossa that corresponds to CP_1 (FP)
7. Medial and lateral poles of the condyle.

All the markers were placed along a plane perpendicular to the horizontal condylar axis that bisected the medial and lateral poles.

2.2.2 True Distance Measurements of the Condyle and Fossa

The following distances were selected as representative measurements to investigate the dimensional accuracy of the condyle and fossa in the horizontal and vertical planes (Figure 2.2, 2.3):

FA to FP = WF (Width of the mandibular fossa)

CA_1 to CP_1 = W1 (Width of the superior aspect of the condylar head)

CA_2 to CP_2 = W2 (Width of the central aspect of the condylar head)

CA_3 to CP_3 = W3 (Width of the inferior aspect of the condylar head)

FS to the midpoint between FA and FP = HF (Height of mandibular fossa)

CA_1 to CA_3 = H1 (Height of anterior aspect of condyle)

CS to the midpoint between CA_3 and CP_3 = H2 (Height of central aspect of condyle)

CP_1 to CP_3 = H3 (Height of posterior aspect of condyle)

The Coordinate Measuring Machine (Starrett Corporation, Athol, MA) was used to determine the true dimensions of the condyle and fossa. The Coordinate Measuring

Machine (CMM) provided values for the X, Y and Z coordinates of each digitized point relative to an established origin and calculates the linear distances between two digitized points. Following initial calibration of the CMM, the markers on the condyle and the fossa were digitized separately using varying orientations of the machine's external probe. A bench vice was used to stabilize the cranium and mandible. Each series of 10 markers was digitized in random order five separate times.

2.2.3 True Distance Measurements of the Joint Space

The following distances were selected as representative measurements to investigate the dimensional accuracy of the joint space (Figure 2.4):

CA_1 to FA = AJS (Anterior joint space)

CS to FS = SJS (Superior joint space)

CP_1 to FP = PJS (Posterior joint space)

An impression of the joint space was obtained using cold cure acrylic resin (Duralay) to provide an imprint of the markers on the articulating surfaces of the condyle and fossa. Using a digital caliper, distances between the markers were measured to the nearest 1/10mm. Each measurement was repeated ten times in random order. Prior to radiographic imaging, the joint space impression was replaced to provide positive seating for the condyle. The maxillary and mandibular teeth were secured using an acrylic splint to ensure a stable and reproducible condyle/fossa relationship (Appendix A).

2.2.4 Tomography

The CommCAT multidirectional tomography unit (Imaging Sciences

International Inc., Roebling, NJ) was used to acquire axially corrected lateral tomographs (Figure 2.5). The central aspect of the condyle was imaged with a slice thickness of 6mm to ensure that all the radiographic markers were included in the tomographic slice. A submentovetex film was taken to calculate the horizontal condylar axis angulation. This angle was defined as the plane formed between the two markers placed on the medial and lateral poles of the condyle and the intermeatal axis (Figure 1.3). The skull was positioned according to the manufacturer's directions to simulate ideal positioning of a patient's head in the tomographic unit. Markings placed on the frontal and lateral aspects of the skull, representing the midsagittal plane and Frankfurt horizontal, assisted in the alignment with the horizontal and vertical laser lights. The skull was repositioned and imaged five times in the tomographic unit.

2.2.5 Panoramic Radiography

Lateral TMJ images were taken with two conventional panoramic radiography units and one digital panoramic radiography unit (Figure 2.6, 2.7, 2.8). TMJ-specific settings were used in each of the units:

Unit 1: OP 100 – Program #6 (Instrumentarium, Tuusula, Finland)

Unit 2: PM 2002 CC Proline – Program #P10 (Planmeca, Helsinki, Finland)

Unit 3: Orthophos DS (digital) – Program #6 (Sorodex, Munich, Germany)

For each panoramic radiography unit, the skull was positioned according to the manufacturers' directions to simulate ideal patient positioning. In general, the skull was centered using the midsagittal plane, while Frankfurt horizontal was maintained parallel to the floor. The reference lines on the skull assisted in the precise alignment of the skull

with the panoramic units' horizontal and vertical light guides. Test exposures were made in each unit to establish values for kV and mA that provided images with sufficient density and contrast for future landmark identification. The skull was repositioned and imaged five times in each of the units.

The Orthophos DS operated with a CCD-sensor with an effective detector array of 138 x 5.9 mm^2 providing an individual pixel size of 45μ. To reduce file size, the pixel size was stored at 90μ. This provided a theoretical spatial resolution of 5.6lp/mm and a total image size of 3000 x 1540 pixels. The signals were acquired at a bit depth of 12 bit (4096 shades of gray), however this was reduced to 8 bit (256 shades of gray) in the default preprocessing procedure.

2.2.6 Radiographic Distance Measurements

Radiographic images from the two conventional panoramic units (Unit 1 and Unit 2) were scanned at a resolution of 600dpi with the Epson Expression 1680 (Epson America, Long Beach, CA). Images from the three panoramic radiography units were digitized separately and each of the 20 images were digitized five times in random order using a University of Alberta custom designed software program (Crushersoft Software, Edmonton, Alberta). This program then generated the radiographic distances in the form of an excel spreadsheet. The average radiographic distances for each unit are reported in Table 2.1.

2.2.7 Magnification Factor and Distortion Index

The magnification factor is the ratio of the radiographic distance to the actual

distance. Comparison of the standard deviation of the true distance measurements with the standard deviation of the radiographic distance measurements revealed that the standard deviations were generally smaller for the true distance measurements. This allowed calculation of the magnification factor for each radiographic distance using the mean of the true distance measurements.

The distortion index is the ratio of the vertical magnification factor to the horizontal magnification factor. The following combinations of vertical and horizontal magnifications were used to calculate the distortion indexes in various areas of the TMJ image: H1W1, H1W2, H1W3, H2W1, H2W2, H2W3, H3W1, H3W2, H3W3, HFWF.

2.2.8 Error of Method

All skull modifications, skull positioning in the panoramic radiography and tomography units, and distance measurements (actual and radiographic) were performed by the principle investigator.

The total error for the distance measurements was a combination of the digitization error and the repeated head positioning error. The total error for each unit ranged from 0.03mm to 0.12mm (CommCAT), 0.05mm to 0.19mm (OP 100), 0.02mm to 0.12mm (PM 2002 CC Proline), and 0.07mm to 0.31mm (Orthophos DS).

2.2.9 Statistical Analysis

A repeated measures ANOVA (Bonferroni pairwise comparisons) was performed to determine if the calculated magnification factor was constant between all horizontal distances (W1, W2, W3, WF) in each imaging unit. The same analysis was performed on

all vertical (H1, H2, H3, HF) and joint space (AJS, SJS, PJS) distances. One sample t-tests were performed to detect differences between the radiographic distortion index and a theoretical distortion index (=1). A distortion index with a value equal to one indicates that there is no distortion and the proportions of the object being imaged are depicted correctly. Significance levels less than 5% were considered to be statistically significant.

2.3 Results

Mean and standard deviation values of the calculated magnification factors for the horizontal, vertical and joint space distances are presented in Table 2.2. The average horizontal magnification factor ranged from 1.17 to 1.30 except for the OP 100, which had an average magnification of 1.56. The average vertical magnification factor ranged from 1.22 to 1.31 and the average joint space magnification factor ranged from 1.10 to 1.29.

Repeated measures ANOVA (Bonferroni pairwise comparisons) of the horizontal magnification factors (W1, W2, W3, WF), vertical magnification factors (H1, H2, H3, HF), and joint space magnification factors (AJS, SJS, PJS) are presented in Tables 2.3, 2.4 and 2.5 respectively. Statistically significant differences were found between the majority of the magnification factors in the horizontal dimension (83%) and in the vertical dimension (67%) for all four units. Similar results were found between the magnification factors of the joint space (83%).

Mean and standard deviation values of the distortion indexes are presented in Table 2.6. One-sample t-tests of the radiographic distortion indexes and the theoretical distortion index are presented in Table 2.7. The majority of distortion indexes for the

CommCAT (90%), PM 2002 CC Proline (90%), and Orthophos DS (60%) were statistically significantly different from the ideal distortion index, while all of the distortion indexes for the OP 100 were significantly different. A repeated measures ANOVA (Bonferroni pairwise comparisons) of distortion indexes revealed that there were significant differences between the OP 100 and the remaining three units (P-value = 0.000), as well as between the CommCAT and the Orthophos DS (P-value = 0.021).

2.4 Discussion

The panoramic image is composed of two central projections, one in the horizontal dimension and one in the vertical dimension. The vertical dimension is dependent on a beam projection that has the x-ray source as the focus, which is similar to the standard central projection of an intraoral radiograph. The horizontal dimension is dependent on a beam projection that has a rotation center as the effective focus and is affected by the velocity of the x-ray beam in relation to the film cassette. [17, 27]

Dimensional accuracy of a panoramic image is determined by the horizontal and vertical magnification. The inherent magnification seen on a panoramic image is dependent upon the position of an object between the x-ray source and the film. In the central plane of the focal trough, the magnification is the same for both the horizontal and vertical dimensions.[7, 28] The average magnification along the central plane of the focal trough has been reported by manufacturers, however structures outside this plane will experience varying degrees of distortion. When an object is displaced from the central plane towards the x-ray source, magnification will increase more in the horizontal than in the vertical dimension because of the difference between the velocity of the film and the

velocity of the x-ray beam. When an object is displaced towards the film cassette, magnification decreases more in the horizontal than the vertical dimension.[24]

The image layers of the panoramic radiography units for the lateral TMJ programs are wider than the tomographic image layer. The reported thickness of the image layer for the Orthophos Plus (panoramic sagittal view) is approximately 38mm. A wider image layer produces less blurring of the adjacent structures.[25] Ludlow et al found that the residual blur is better defined in panoramic images and may be more easily confused with actual joint anatomy.[25] In this study, utilizing the center of the radiopaque stainless steel balls for digitization reduced the subjectivity of radiographic landmark identification.

Magnification and distortion of a panoramic image are influenced by mandibular morphology and head position. Mandibular morphology was kept constant by the utilization of one TMJ from a single skull. The skull was positioned in the tomography and panoramic radiography units according to the manufacturers' directions to simulate ideal patient positioning. Therefore, the observed changes in magnification and distortion of the lateral TMJ images are the result of differences in the imaging geometry of each radiographic unit.

The results of this study revealed that the OP 100 had the largest average horizontal magnification factor (1.56), which was nearly 25% greater than the other units. Although the manufacturer's directions for patient positioning were strictly followed, the large horizontal magnification suggested that the right TMJ of the skull was not located within the central plane of the focal trough. The increase in horizontal magnification relative to the vertical magnification suggested that the right TMJ was displaced towards the x-ray source. Scarfe et al. found similar results for horizontal magnification during

their empirical investigation of the OP 100's imaging characteristics.[29] In their study, the horizontal magnification factor varied from 1.01 to 1.63 within the focal trough.

For each panoramic radiography unit, there were statistically significant differences between the majority of magnification factors in the horizontal and vertical dimensions. These results suggested that magnification was not constant in either dimension. The OP 100 demonstrated the largest variation between magnification factors for both the horizontal (-0.026 to -0.115) and vertical dimensions (0.004 to 0.048). Similar results were found for magnification of the joint space, suggesting that magnification was not constant between the AJS, SJS, and PJS. The PM 2002 CC Proline demonstrated the largest difference between joint space magnification factors with a range of -0.003 to -0.110. It should be noted that the AJS and PJS are oblique measurements and the overall magnification is a combination of the magnifications in the horizontal and vertical dimensions. No trends were observed between the panoramic radiography units; therefore the differences in magnification are machine-dependent.

Studies have shown that axially corrected tomographs provide accurate and reliable morphologic and morphometric information about the osseous components of the temporomandibular joint and its spatial relationships.[30-37] The results of this study revealed that there were statistically significant differences between magnification factors in the horizontal and vertical dimensions of axially corrected tomographs. Similarly, there was statistically significant variation in magnification between the AJS, SJS, and PJS. The differences between the joint space magnification factors ranged from -0.127 to 0.060, which was the largest of all four units combined. On lateral tomographs, a comparison of the radiographic dimensions of the joint space is often used to determine

the position of the condyle within the fossa.[38-43] Hatcher et al found that the width of the joint space in the sagittal plane varied from the medial to the lateral regions in 36% of all joints examined.[44] Therefore, the combination of the variation in radiographic magnification and the anatomical variation in three dimensions may preclude the use of tomographs and lateral TMJ panoramic radiographs for the classification of condylar position.

The distortion index was calculated to determine the presence or absence of distortion in a specified area of the radiographic image. For each of the units, statistically significant differences were found for the majority of distortion indexes. The OP 100 was found to have the largest amount of distortion with distortion indexes as low as 0.782. A distortion index of less than one indicated that the horizontal magnification was greater than the vertical magnification. Visually, this magnitude of distortion was evident when the lateral TMJ images from the OP 100 were compared to the tomographs.

The CommCAT had distortion indexes of 0.981 to 0.998 for the condyle and 1.017 for the fossa. The condyle demonstrated greater magnification in the horizontal dimension than the vertical dimension, while the fossa demonstrated the opposite effect. If an object lies within the tomographic plane or the image layer, the tomographic image should essentially be free of distortion. It is possible that the markers on the surface of the condyle and fossa were not entirely located within the 6mm image layer. Ahlqvist et al examined radiographic distortion of the mandibular fossa in conventional tomography and found that the angulation of parts of the roof and posterior wall in relation to the established imaging planes makes them highly susceptible to distortion.[45] Of all the units, the CommCAT demonstrated the least amount of distortion (average mean difference of

the absolute values of the distortion indexes = 0.012), followed by the Orthophos DS (0.013), PM 2002 CC Proline (0.018), and OP 100 (0.195).

Although statistically significant differences in magnification factors and distortion indexes were found for all the radiographic units, many of these differences are small. If these lateral TMJ images are to be utilized in a clinical situation, it is important to determine whether these differences have clinically any significance. For example, a horizontal magnification difference of 2.7% for the CommCAT would correlate to a size difference of approximately 0.2 to 0.4mm on the tomographic image in the horizontal dimension. Similarly, a distortion index of 0.981 for the CommCAT would correlate to a size difference of 0.2 to 0.3mm between the horizontal and vertical dimensions. Differences of this magnitude would be very difficult to detect in a clinical situation and are likely beyond the limits of perceptibility of any practitioner. A review of the current literature did not reveal any studies that investigated clinically significant tolerance limits for radiographic magnification or distortion.

The results of this study can only be applied to the particular models of panoramic radiography units utilized. In addition, the use of a single skull does not allow for extrapolation of the results of this study to the population in general. However, the principles of magnification and distortion in panoramic radiography are universal.

2.5 Conclusion

The following conclusions can be drawn from this study:

1. Statistically significant variation in magnification was found in the horizontal and vertical dimensions of lateral TMJ images from the tomography unit and the three

panoramic radiography units. The variation in magnification was machine dependent.

2. Statistically significant variation in magnification was found within the joint space on the lateral TMJ images of the tomography unit and the three panoramic radiography units. The variation in magnification was machine dependent.
3. A statistically significant amount of dimensional distortion was found on the lateral TMJ images from all the units. The lateral TMJ images from the CommCAT were the most dimensionally accurate, followed by the Orthophos DS, PM 2002 CC Proline, and the OP 100.
4. Further research needs to be conducted to determine clinically significant tolerance limits for radiographic magnification and distortion.
5. Lateral TMJ images from the PM 2002 CC Proline and the Orthophos DS may be suitable for the initial radiographic examination of the osseous components of the TMJ. However, practitioners should be aware of the limitations of this technique, particularly the potential for dimensional distortion.

Figure 2.1: Marker Location

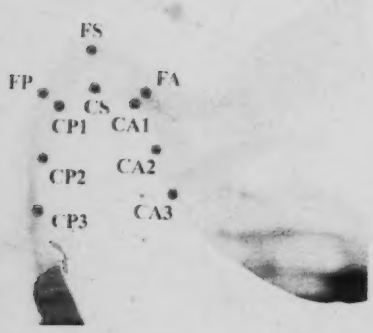

Figure 2.2: Horizontal distance Measurements

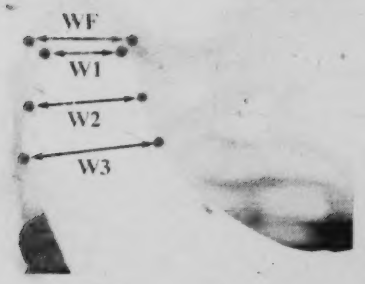

Figure 2.3: Vertical distance Measurements

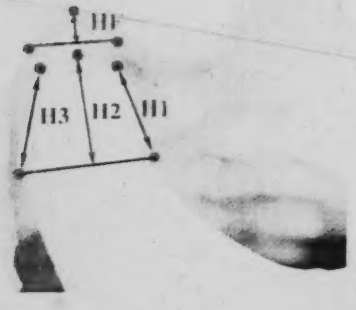

Figure 2.4: Joint space distance Measurements

Figure 2.5: Lateral TMJ image CommCAT

Figure 2.6: Lateral TMJ image OP 100

Figure 2.7: Lateral TMJ image PM 2002 CC Proline

Figure 2.8: Lateral TMJ image Orthophos DS

Table 2.1 Mean and standard deviation values for distance measurements (in mm)*

Distance	ACTUAL DISTANCE		RADIOGRAPHIC DISTANCE (4 MACHINES)							
			Tomography		OP 100		PM 2002 CC Proline		Orthophos 3 DS	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
W1	6.88	0.04	8.83	0.06	10.81	0.14	8.45	0.09	8.91	0.19
W2	6.85	0.08	8.84	0.06	10.83	0.19	8.53	0.07	8.88	0.22
W3	7.70	0.02	9.81	0.03	12.36	0.15	9.67	0.08	9.79	0.23
WF	10.34	0.04	13.10	0.12	15.43	0.16	12.08	0.12	13.21	0.31
H1	9.28	0.01	11.81	0.06	11.80	0.05	11.46	0.04	12.14	0.07
H2	12.60	0.00	15.95	0.05	15.98	0.05	15.47	0.05	16.48	0.09
H3	11.20	0.02	14.19	0.08	14.06	0.05	13.68	0.04	14.52	0.08
HF	4.07	0.12	5.23	0.06	5.31	0.07	5.02	0.04	5.25	0.07
AJS	2.00	0.03	2.31	0.07	2.58	0.07	2.20	0.04	2.56	0.09
SJS	3.56	0.02	4.56	0.05	4.42	0.05	4.32	0.02	4.50	0.09
PJS	3.36	0.04	4.11	0.12	4.06	0.07	3.72	0.06	4.05	0.10

* Based on 25 measurements for each machine and 5 measurements for each actual distance

Table 2.2 Mean and standard deviation values for the calculated magnification factor*

Distance	MAGNIFICATION FACTOR (4 MACHINES)							
	Tomography		OP 100		PM 2002 CC Proline		Orthophos DS	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
W1	1.28	0.01	1.57	0.02	1.23	0.01	1.30	0.03
W2	1.29	0.01	1.58	0.03	1.25	0.01	1.30	0.03
W3	1.28	0.00	1.61	0.02	1.26	0.01	1.27	0.03
WF	1.26	0.01	1.49	0.02	1.17	0.01	1.28	0.03
H1	1.27	0.01	1.27	0.01	1.24	0.00	1.31	0.01
H2	1.27	0.00	1.27	0.00	1.23	0.00	1.31	0.01
H3	1.27	0.01	1.26	0.00	1.22	0.00	1.30	0.01
HF	1.29	0.02	1.30	0.02	1.23	0.01	1.29	0.02
AJS	1.16	0.04	1.29	0.03	1.10	0.02	1.29	0.04
SJS	1.28	0.01	1.24	0.02	1.21	0.01	1.26	0.03
PJS	1.22	0.04	1.21	0.02	1.11	0.02	1.21	0.03

Magnification factor = radiographic distance/actual distance

* Based on 25 measurements for each machine

Table 2.3 Repeated measures ANOVA (Bonferroni pairwise comparisons) of the horizontal magnification factors*

Distance		Tomography		OP 100		PM 2002 CC Proline		Orthophos 3 DS	
A	*b*	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value
WF	W1	-0.019	0.000*	-0.079	0.000*	-0.060	0.000*	-0.018	0.000*
WF	W2	-0.027	0.000*	-0.089	0.000*	-0.078	0.000*	-0.020	0.000*
WF	W3	-0.011	0.004*	-0.115	0.000*	-0.090	0.000*	0.005	1.000
W1	W2	-0.008	0.073	-0.098	0.787	-0.017	0.000*	0.002	1.000
W1	W3	0.009	0.008*	-0.036	0.000*	-0.029	0.000*	0.023	0.000*
W2	W3	0.016	0.000*	-0.026	0.000*	-0.012	0.000*	0.025	0.000*

Mean difference = (magnification of distance *a*) – (magnification of distance *b*)
* A P-value of less than 0.050 is considered statistically significant

Table 2.4 Repeated measures ANOVA (Bonferroni pairwise comparisons) of the vertical magnification factors*

Distance		Tomography		OP 100		PM 2002 CC Proline		Orthophos 3 DS	
a	*b*	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value
HF	H1	0.013	0.131	0.032	0.000*	-0.002	1.000	-0.019	0.002*
HF	H2	0.020	0.000*	0.036	0.000*	0.004	1.000	-0.018	0.003*
HF	H3	0.019	0.000*	0.048	0.000*	0.011	0.006*	-0.007	1.000
H1	H2	0.007	0.012*	0.004	0.898	0.007	0.000*	0.001	1.000
H1	H3	0.006	1.000	0.016	0.000*	0.014	0.000*	0.012	0.000*
H2	H3	0.001	1.000	0.012	0.000*	0.007	0.000*	0.011	0.000*

Mean difference = (magnification of distance *a*) – (magnification of distance *b*)
* A P-value of less than 0.050 is considered statistically significant

Table 2.5 Repeated measures ANOVA (Bonferroni pairwise comparisons) of the joint space magnification factors*

Distance		Tomography		OP 100		PM 2002 CC Proline		Orthophos 3 DS	
a	*b*	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value
AJS	SJS	-0.127	0.000*	0.051	0.000*	-0.110	0.000*	0.021	1.000
AJS	PJS	-0.067	0.000*	0.085	0.000*	-0.003	1.000	0.079	0.000*
SJS	PJS	0.060	0.000*	0.034	0.000*	0.107	0.000*	0.058	0.000*

Mean difference = (magnification of distance *a*) – (magnification of distance *b*)
* A P-value of less than 0.050 is considered statistically significant

Table 2.6 Mean and standard deviation values for calculated distortion index

Ratio	RADIOGRAPHIC DISTORTION INDEX (4 MACHINES)							
	Tomography		OP 100		PM 2002 CC Proline		Orthophos 3 DS	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
H1W1	0.992	0.007	0.810	0.010	1.005	0.010	1.012	0.018
H1W2	0.987	0.009	0.805	0.013	0.992	0.007	1.009	0.022
H1W3	0.998	0.005	0.792	0.009	0.982	0.007	1.029	0.021
H2W1	0.986	0.007	0.807	0.010	1.000	0.010	1.010	0.021
H2W2	0.981	0.008	0.802	0.014	0.986	0.007	1.008	0.025
H2W3	0.993	0.004	0.789	0.009	0.977	0.006	1.029	0.024
H3W1	0.987	0.009	0.800	0.010	0.994	0.012	1.001	0.019
H3W2	0.981	0.010	0.795	0.014	0.981	0.009	1.000	0.023
H3W3	0.994	0.005	0.782	0.009	0.971	0.009	1.020	0.022
HFWF	1.017	0.017	0.874	0.011	1.055	0.009	1.010	0.027

Distortion index = vertical magnification factor/horizontal magnification factor
A distortion index *greater* than 1.000 indicates that the vertical magnification is greater than the horizontal magnification
A distortion index *less* than 1.000 indicates that the horizontal magnification is greater than the vertical magnification

Table 2.7 One sample t-tests of the distortion indexes*

Ratio	Tomography		OP 100		PM 2002 CC Proline		Orthophos DS	
	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value
H1W1	-0.008	0.000*	-0.190	0.000*	0.006	0.013*	0.011	0.007*
H1W2	-0.014	0.000*	-0.195	0.000*	-0.008	0.000*	0.009	0.036*
H1W3	-0.002	0.091	-0.208	0.000*	-0.018	0.000*	0.029	0.000*
H2W1	-0.014	0.000*	-0.193	0.000*	-0.000	0.932	0.010	0.019*
H2W2	-0.019	0.000*	-0.198	0.000*	-0.014	0.000*	0.009	0.065
H2W3	-0.007	0.000*	-0.211	0.000*	-0.023	0.000*	0.029	0.000*
H3W1	-0.013	0.000*	-0.201	0.000*	-0.006	0.022*	0.001	0.532
H3W2	-0.019	0.000*	-0.205	0.000*	-0.020	0.000*	0.000	0.696
H3W3	-0.006	0.000*	-0.218	0.000*	-0.029	0.000*	0.020	0.000*
HFWF	0.017	0.000*	-0.126	0.000*	0.056	0.000*	0.010	0.050

Mean difference = radiographic distortion index - theoretical distortion index (1)
*A P-value of less than 0.050 is considered statistically significant

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Chapter Three

Research Paper Two

A Comparative Study of Radiographic Condylar Shape between Lateral Temporomandibular Joint Images from Three Panoramic Radiography Units and Axially Corrected Multidirectional Tomography

3.1 Introduction:

Conventional tomography has been recommended by the American Academy of Oral and Maxillofacial Radiology to evaluate the osseous components of the temporomandibular joint (TMJ) because of the cost and the relatively high risk of radiation exposure associated with computed tomography. [1] On a tomographic image, the appearance of the shape of the condyle is normally smooth and continuous. Erosions (pitted irregular contours of the bony surface), flattening of the condyle, and osteophyte formation are signs of degenerative changes. These radiographic findings are commonly associated with osteoarthritic changes in the TMJ.[2,3]

Tomography provides both lateral and frontal views of the TMJ. In the axially corrected technique, the horizontal condylar axis angulation is calculated using a submentovertex film. This individualized technique allows precise positioning of the x-ray beam relative to the anatomy of the condyle and produces the most reliable morphometric and morphologic information regarding the osseous components of the TMJ. [4, 5]

Unlike axially corrected tomography, the direction of the x-ray beam in panoramic radiography is not parallel to the long axis of the condyle, resulting in an oblique section of the TMJ. On a panoramic image, the lateral condylar pole is visualized as the anterior border of the condyle, the posterior pole is visualized correctly as the posterior border of the condyle, and the medial pole is superimposed over the center of the condyle near the posterior condylar border. In some instances, the medial pole may be superimposed over the posterior border of the condyle.[6, 7] As a result, interpretation of osseous changes can only be made on the lateral pole of the condyle.[6]

Newer generation panoramic radiography units have specialized TMJ programs that provide both lateral and frontal views of the TMJ. The programs are designed with an arbitrary correction for horizontal condylar axis angulation based on population norms.[8] However, the inherent magnification in the horizontal and vertical dimensions of the x-ray beam relative to the TMJ anatomy can lead to substantial image distortion.[9] While distortion of the size of an object on a panoramic radiograph has often been described, distortion of shape is more difficult to define and quantify.[10-16]

A quantitative analysis of condylar shape and its variation can be accomplished by a mathematical method that involves a curve-fitting procedure. This method computes a mathematical function, which is used to describe the outline of the condyle. The features of the outline can then be analyzed independently of its size and spatial orientation. A similar curve-fitting procedure (Fourier series) was used by Ferrario et al. to describe the asymmetry between right and left mandibular condyles on panoramic radiographs.[17]

The purpose this study was to compare the radiographic shape of the condyle between lateral TMJ images from axially corrected tomography and three panoramic radiography units.

3.2 Materials and Methods

3.2.1 Skull Testing Device Design

A dry human skull with an intact temporomandibular joint and a stable occlusion was selected. Radiopaque markers consisting of stainless steel balls approximately 1.58mm in diameter were used as reference points. Four markers were fixed onto the

surface of the right condyle following preparation with a #2 round bur. Two markers were placed on the medial (MP) and lateral poles (LP) of the condyle to aid in determining the horizontal condylar axis angulation during tomography, while two markers were placed on the anterior (CA_3) and the posterior (CP_3) surfaces of the condyle. A reference line connecting CA_3 and CP_3 was used to delineate the condyle from the ramus on the radiographic image (Figure 3.1).

The mandibular fossa was remodeled with cold cure acrylic resin to provide positive seating of the condyle. The maxillary and mandibular teeth were secured using an acrylic splint to ensure a stable and reproducible condyle/fossa relationship (Appendix A).

3.2.2 Tomography

The CommCAT multidirectional tomography unit (Imaging Sciences International Inc., Roebling, NJ) was used to obtain axially corrected lateral tomographs (Figure 3.2). The central aspect of the condyle was imaged with a slice thickness of 6mm to ensure that the radiographic markers on the anterior and posterior surfaces were included in the tomographic slice. A submentovetex film was taken to calculate the horizontal condylar axis angulation relative to the intermeatal axis. The skull was positioned according to the manufacturer's directions to simulate the ideal position of a patient's head in the tomographic unit. Markings placed on the frontal and lateral aspects of the skull, representing the midsagittal plane and Frankfurt horizontal, assisted in the alignment with the horizontal and vertical laser lights. The skull was repositioned and imaged five times in the tomographic unit.

3.2.3 Panoramic Radiography

Lateral TMJ images were taken with two conventional panoramic radiography units and one digital panoramic radiography unit (Figure 3.3, 3.4, 3.5). TMJ-specific settings were used in each of the units:

Unit 1: OP 100 – Program #6 (Instrumentarium, Tuusula, Finland)

Unit 2: PM 2002 CC Proline – Program #P10 (Planmeca, Helsinki, Finland)

Unit 3: Orthophos DS (digital) – Program #6 (Sorodex, Munich, Germany)

For each panoramic radiography unit, the skull was positioned according to the manufacturers' directions to simulate ideal patient positioning. In general, the skull was centered using the midsagittal plane, while Frankfurt horizontal was maintained parallel to the floor. The reference lines on the skull assisted in the precise alignment of the skull with the panoramic units' horizontal and vertical light guides. Test exposures were made in each unit to establish values for kV and mA that provided images with sufficient density and contrast for future landmark identification. The skull was repositioned and imaged five times in each of the panoramic radiography units.

The Orthophos DS operated with a CCD-sensor with an effective detector array of 138 x 5.9 mm^2 providing an individual pixel size of 45μ. To reduce file size, the pixel size was stored at 90μ. This provided a theoretical spatial resolution of 5.6lp/mm and a total image size of 3000 x 1540 pixels. The signals were acquired at a bit depth of 12 bit (4096 shades of gray), however this was reduced to 8 bit (256 shades of gray) in the default preprocessing procedure.

3.2.4 Radiographic Shape Analysis

Radiographic images from the two conventional panoramic units (Unit 1 and Unit 2) were scanned at a resolution of 600dpi with the Epson Expression 1680 (Epson America, Long Beach, CA). The outline of the condyle was digitized and mathematically reconstructed using a University of Alberta custom designed software program (Crushersoft Software, Edmonton, Alberta). The outlines were truncated at a reference line that delineated the condyle from the ramus. Images from the three panoramic radiography units were digitized separately and each of the twenty images were digitized three times in random order. The software program then generated an average condylar shape for each image.

A mathematical representation of an irregular shape such as a condyle was done by breaking the curve outline into several smaller curves and representing each as a third order polynomial, or cubic spline curve. Figure 3.6 shows a pattern of data points connected by a number of spline curves (the connecting lines). Spline curves are used to create an outline that not only passes through each data point, but is also smooth at each data point. This is important to allow computation of useful mathematical quantities such as area, perimeter and centroid (center of gravity). The mathematical representation of shape allowed for the numerical evaluation of line integrals to compute these quantities. For simplicity, a measure of the area was computed using pixel counting of the shape as displayed on the computer screen.

An average condylar shape for each radiographic image was generated from the combination of the three digitized outlines. Each outline was traversed in equal steps, yielding a set of discrete outline points. Each outline point was then averaged with the

corresponding points from the two other outlines to yield a set of points describing the 'averaged' outline. A new set of spline curves was calculated to represent this 'average' condylar shape.

To determine differences between two condylar shapes, one condylar shape was normalized mathematically relative to a second with respect to its size (area) and orientation. Scaling shapes to normalize area was accomplished by adjusting the radial distance from the computed centroid to each of the data points. This retains the shape of the condyle while scaling as required. Operations are reversible meaning that scaling an object by a factor of 0.8 and then scaling by a factor of 1.25 yields the same shape, within some numerical tolerance. Orientation was normalized by first translating the centroidal position of one condylar shape to coincide with the other and then rotating all the control points about the centroid to make the reference lines parallel. These operations were possible by simply translating or rotating all the original data points that specified the shape. The spline curve fit was repeated on the new set of data points to yield a new mathematical representation of the translated and rotated condylar shape.

Shape comparisons were performed by superimposing the normalized condylar shapes on the reference line. The difference in shape was expressed as a percentage of the sum of dissimilar areas and was generated in the form of an excel spreadsheet. As shape area comparison was the only area-related quantity of interest, the units of area (the number of pixels or units of length squared) were not important, being that they were lost in the ratio calculations. To determine condylar shape differences for each panoramic radiography unit, the average condylar shapes from the five tomographic images were compared to the corresponding average condylar shapes from the panoramic images (ie.

CommCAT image 1 vs. OP 100 image 1, CommCAT image 2 vs. OP 100 image 2). As a result, five shape comparisons out of a possible 15 combinations were completed for each panoramic radiography unit. Figure 3.7, 3.8, 3.9 are graphical representations of the shape comparisons between image five of the CommCAT and each of the panoramic radiography units after mathematical normalization of size and orientation. Although the shape comparisons of image five are presented, similar results were observed for image one to four.

3.2.5 Error of Method

For the shape difference measurements, the total error for each unit was 1.0%(CommCAT), 0.7%(OP 100), 0.9%(PM 2002 CC Proline), and 1.5% (Orthophos DS). Other negligible errors could be derived from the mathematical procedure involved in reconstruction of the condylar outline.

3.2.6 Statistical Analysis

One sample t-tests were performed to determine statistical significance of the shape differences for each panoramic radiography unit. Differences between the condylar shape of the tomography unit and the three panoramic radiography units were compared to a theoretical shape difference of zero. Assuming that the tomographic technique produces a lateral TMJ image with no distortion, any statistically significant deviations from a shape difference of zero percent suggests that the panoramic image of the condyle is affected by form distortion. Significance levels less than 5% were considered to be statistically significant.

3.3 Results

Differences between the average condylar shapes of the tomographs and the panoramic radiographs, along with the mean and standard deviation values are presented in Table 3.1. One sample t-tests to determine the statistical significance of the shape differences for each panoramic radiography unit are presented in Table 3.2. The results revealed that the shape differences between the condylar forms of the tomographs and all three panoramic radiographs were statistically significant. A repeated measures ANOVA (Bonferroni pairwise comparisons) of shape differences between the three panoramic radiography units revealed that there were statistically significant differences between all machines except the OP 100 and the Orthophos DS (P-value = 0.167).

3.4 Discussion

Distortion of object morphology or shape is referred to as *form distortion*. The basic characteristics of form distortion in panoramic radiography have been investigated by Sjoblom et al.[18] The distortion of four two-dimensional objects (square, circle, triangle, and a rhombus) was analyzed mathematically by test exposures at varying distances from the central plane of the focal trough. The authors found that the circular object was reproduced as an ellipse when the object was placed outside the central plane. The degree of distortion of the circular object was dependent on the distance from the central plane. Welander et al found that there was considerable tolerance towards form distortion for the lateral regions of a panoramic image compared to the anterior region.[19] Form distortion of a three-dimensional object (sphere) in panoramic radiography was investigated mathematically and experimentally by Tronje et al. The authors found that

form distortion of a sphere closely coincides with the distortion calculated for a circular object. They suggested that rounded anatomic structures that are positioned within the central plane of the focal trough should be correctly reproduced on a panoramic radiograph.

The results of this study indicated that there were statistically significant differences in condylar shape between tomographic images and panoramic images. These differences are independent of the size and orientation of the condyle on the radiographic image. The Orthophos DS demonstrated the largest average difference in condylar shape (24.8%). It is likely that the x-ray beam angulation of the Orthophos DS was more oblique relative to the horizontal long axis of the condyle in comparison to the OP 100 and the PM 2002 CC Proline. Subjective assessment of lateral TMJ images from each of the panoramic radiography units suggested that the anterior contour of the condyle on the radiographic image had the greatest variation in shape.

Although the lateral TMJ programs are designed to provide arbitrary corrections for horizontal condylar axis angulation, the panoramic images may not be true lateral views of the TMJ as in axially corrected tomography. As a result, the shape of the condyle may vary depending upon the angulation of the x-ray beam relative to the TMJ. Distortion of the shape of the condyle could potentially result in misinterpretation of the radiographic image, especially since flattening of the condyle is associated with degenerative changes. [20] Furthermore, the cortical bone may not appear as distinct on the panoramic TMJ images compared to the tomographic images because of the thickness of the image layer. This loss of sharpness may contribute to the shape differences seen for

each panoramic radiography unit, particularly since digitizing these images was more difficult despite the image enhancing capabilities of the software program.

The results of this study can only be applied to the particular models of panoramic radiography units utilized. In addition, the use of a single skull does not allow for extrapolation of the results of this study to the population in general. Although the manufacturer's directions for patient positioning were strictly followed for each panoramic radiography unit, the position of the TMJ within the focal trough could affect the shape of the condyle as depicted on a panoramic image. A companion study demonstrated that at the ideal head position, lateral TMJ images from the OP 100 had significant size distortion with greater magnification in the horizontal dimension than the vertical dimension.[9] As a result, the condyle appeared foreshortened which directly impacted the overall shape of the condyle.

3.5 Conclusion

The following conclusions can be drawn from this study:

1. A statistically significant difference in the shape of the condyle was found between the lateral TMJ images from the tomography unit and each of the three panoramic radiography units. The lateral TMJ images from the PM 2002 CC Proline demonstrated the smallest shape difference, followed by the OP 100 and the Orthophos DS.
2. If panoramic radiography is to be used for the initial radiographic examination of the osseous structures of the TMJ, practitioners should be aware of the potential for shape distortion of the condyle due to the nonorthogonal alignment of the x-ray beam.

3. Further radiographic examination that provides detailed visualization of the osseous structures such as conventional tomography should be requested if the information provided by the clinical examination and the panoramic TMJ image suggest the presence of degenerative changes.

Figure 3.1: Marker Location

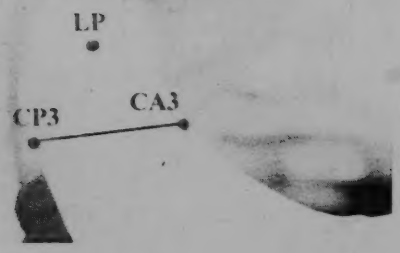

Figure 3.2: Lateral TMJ images CommCAT

Figure 3.3: Lateral TMJ images OP 100

Figure 3.4: Lateral TMJ images PM 2002 CC Proline

Figure 3.5: Lateral TMJ images Orthophos DS

Figure 3.6: Data points connected with spline curves

Figure 3.7: CommCAT vs. OP 100 (normalized)

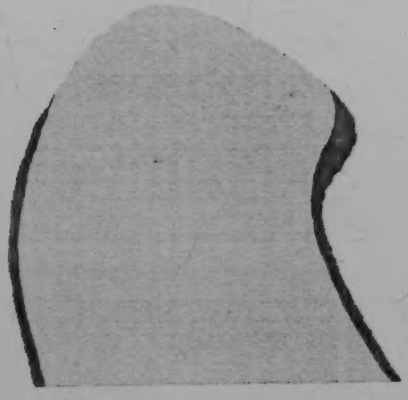

Figure 3.8: CommCAT vs. PM 2002 CC Proline (normalized)

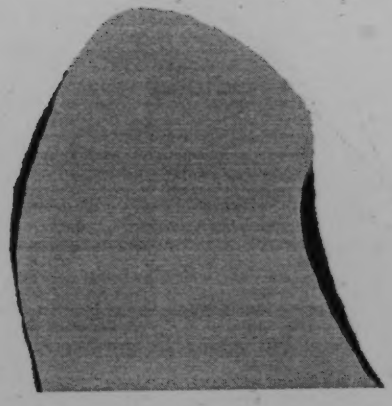

Figure 3.9: CommCAT vs. Orthophos DS (normalized)

Table 3.1 Shape differences between the average condylar forms from tomography and each of the three panoramic radiography units (%)

Image Number	Tomography vs OP 100	Tomography vs. PM 2002 CC Proline	Tomography vs. Orthophos DS
1	23.8	17.3	22.6
2	15.2	14.2	20.1
3	19.3	14.5	25.5
4	15.7	11.6	27.4
5	13.6	9.6	27.4
Mean ± S.D.	17.5 ± 4.1	13.4 ± 3.0	24.8 ± 2.9

Table 3.2 One sample t-test comparisons of shape differences for each of the three panoramic radiography units*

Tomography vs OP 100		Tomography vs. PM 2002 CC Proline		Tomography vs. Orthophos DS	
t-Value	P-value	t-Value	P-value	t-Value	P-value
9.6	0.001*	10.2	0.001*	19.1	0.001*

Test value = 0% (theoretical shape difference)

* A P-value of less than 0.050 is considered statistically significant

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Chapter Four

Research Paper Three

The Effect of Horizontal and Vertical Head Rotation on the Dimensions of the Temporomandibular Joint and the Shape of the Condyle from Lateral TMJ Images of Three Panoramic Radiography Units

4.1 Introduction

In recent years, many panoramic radiography units have integrated specialized programs that provide both lateral and frontal views of the temporomandibular joint (TMJ). Panoramic radiography is a valuable tool for the initial radiographic imaging of the TMJ, with the understanding that it is not suitable for detailed visualization of osseous structures.[1-4] Like any panoramic image, these specialized TMJ images have an inherent amount of magnification in the both the vertical and horizontal dimensions that can lead to radiographic distortion.[5] Distortion of the object morphology or shape is referred to as *form distortion* and distortion of the size of an object is referred to as *area distortion*.[6, 7]

To minimize distortion on a panoramic radiograph, the patient should be positioned such that the dental arches including the TMJ are located within the central plane of the focal trough.[8] Structures outside this plane will experience varying degrees of distortion. Magnification will increase more in the horizontal than the vertical dimension when the TMJ is displaced from the central plane towards the x-ray source, while magnification decreases more in the horizontal than the vertical dimension when the TMJ is displaced towards the film cassette.[8]

Schiff et al. reported that the most frequent errors in panoramic radiography occurred in patient positioning.[9] Of the 1000 radiographs examined, the relative frequency of positioning errors were as follows: 14% chin too low, 4% head tilted, 4% head turned, and 1% chin too high. Ruf and Pancherz evaluated the effects of varying skull position on the panoramic image of the TMJ.[10] The authors found that to a large extent, the size, form and position of the condyle was affected by changes in skull

position. In particular, retroclination of the skull resulted in simulation of anterior condylar flattening and osteophytic formation. The authors concluded that because anterior condylar flattening and the presence of osteophytes are among the classic radiographic signs of degenerative TMJ changes, the distortion effects in panoramic radiography may be misinterpreted as signs of TMJ disease.

It is reasonable to suggest that panoramic TMJ-specific images may also be susceptible to significant area and form distortion from patient positioning errors. The purpose of this in vitro study was to determine the effect of varying horizontal and vertical head rotation on the lateral TMJ images from three panoramic radiography units, and to compare these findings to an ideal head position. Specifically, the effects on the dimensional accuracy of the TMJ and radiographic condylar shape were evaluated.

4.2 Materials and Methods

4.2.1 Skull Testing Device Design

A dry human skull with an intact temporomandibular joint (TMJ) and a stable occlusion was selected. Radiopaque markers consisting of stainless steel balls approximately 1.58mm in diameter were used as reference points. These markers were fixed onto the surface of the right condyle following preparation with a #2 round bur. The location of the markers on the surfaces of the condyle and fossa are as follows:

1. Most superior point of the condyle (CS)
2. Three points along the anterior surface of the condyle (CA_1, CA_2, and CA_3)
3. Three points along the posterior surface of the condyle that correspond to CA_1, CA_2, and CA_3 (CP_1, CP_2, and CP_3) .

4. Most superior point of the mandibular fossa (FS)
5. A point along the anterior surface of the mandibular fossa that corresponds to CA_1 (FA)
6. A point along the posterior surface of the mandibular fossa that corresponds to CP_1 (FP)

For analysis of condylar shape, two markers corresponding to CA_3 and CP_3 were placed on the surface of the condyle. A reference line connecting the two markers was used to delineate the condyle from the ramus on the radiographic image. For analysis of TMJ dimensions, the remaining eight markers were fixed onto the surface of the condyle. All the markers were placed along a plane perpendicular to the horizontal condylar axis that bisected the mesial and lateral poles.

4.2.2 True Distance Measurements of the Condyle and Fossa

The following distances were selected as representative measurements to investigate the dimensional accuracy of the condyle and fossa in the horizontal and vertical planes:

FA to FP = WF (Width of the mandibular fossa)

CA_1 to CP_1 = W1 (Width of the superior aspect of the condylar head)

CA_2 to CP_2 = W2 (Width of the central aspect of the condylar head)

CA_3 to CP_3 = W3 (Width of the inferior aspect of the condylar head)

FS to the midpoint between FA and FP = HF (Height of mandibular fossa)

CA_1 to CA_3 = H1 (Height of anterior aspect of condyle)

CS to the midpoint between CA_3 and CP_3 = H2 (Height of central aspect of condyle)

CP_1 to CP_3 = H3 (Height of posterior aspect of condyle)

The Coordinate Measuring Machine (CMM) (Starrett Corporation, Athol, MA) was used to determine the true dimensions of the condyle and fossa. The CMM provides values for the X, Y and Z coordinates of each digitized point relative to an established origin and calculates the linear distances between two digitized point. Following initial calibration of the CMM, the markers on the condyle and the fossa were digitized separately using varying orientations of the machine's external probe. A bench vice was used to stabilize the cranium and mandible. Each series of 10 markers was digitized in random order five separate times.

4.2.3 True Distance Measurements of the Joint Space

The following distances were selected as representative measurements to investigate the dimensional accuracy of the joint space:

CA_1 to FA = AJS (Anterior joint space)

CS to FS = SJS (Superior joint space)

CP_1 to FP = PJS (Posterior joint space)

An impression of the joint space was taken using cold cure acrylic resin (Duralay) to provide an imprint of the markers on the articulating surfaces of the condyle and fossa. Using a calibrated digital caliper, distances between the markers were measured to the nearest 1/10mm. Each measurement was repeated ten times in random order. Prior to radiographic imaging, the joint space impression was replaced to provide positive seating

of the condyle. The maxillary and mandibular teeth were secured using an acrylic splint to ensure a stable and reproducible condyle/fossa relationship (Appendix A).

4.2.4 Skull Holder

A custom designed radiolucent skull holder (Mechanical Engineering, University of Alberta) was constructed as described by Mckee et al. to ensure reproducible rotation of the skull testing device about a horizontal and vertical axis (Appendix B).[11] The skull holder consisted of 3 components:

1. A hollow cylinder - permanently attached to the skull at the foramen magnum.
2. A solid cylinder - precision machined end attached to the hollow cylinder and connected at its base via internal screw threads to the mounting screw on the camera tripod.
3. Camera tripod - fully adjustable in the horizontal and vertical planes

4.2.5 Panoramic Radiography

Lateral TMJ images were taken with two conventional panoramic radiography units and one digital panoramic radiography unit:

Unit 1: OP 100 – Program #6 (Instrumentarium, Tuusula, Finland)

Unit 2: PM 2002 CC Proline – Program #P10 (Planmeca, Helsinki, Finland)

Unit 3: Orthophos DS (digital) – Program #6 (Sorodex, Munich, Germany)

For each panoramic radiography unit, the skull was positioned according to the manufacturers' instructions to simulate ideal patient positioning. In general, the skull was centered using the midsagittal, while Frankfurt horizontal was maintained parallel to the

floor. Simulation of common patient positioning errors was achieved by rotation of the skull in the horizontal and vertical planes. The skull was repositioned five separate times at each of the following five head positions in random order:

1. Ideal Position - 0° horizontal rotation: 0° vertical rotation
2. 5° right - 5° right horizontal rotation: 0° vertical rotation
3. 5° left - 5° left horizontal rotation: 0° vertical rotation
4. 5° up (retroclination) - 0° horizontal rotation: 5° 'head up' vertical rotation
5. 5° down (anteclination) - 0° horizontal rotation: 5° 'head down' vertical rotation

For rotations in the horizontal plane (about a vertical axis of rotation at the center of foramen magnum), parallel markings were placed 5° degrees to the right and left of the midsagittal plane. These markings assisted in the alignment of the skull with the panoramic units' vertical light guide, while maintaining Frankfort horizontal parallel with the horizontal light guide. For rotations in the vertical plane (about a horizontal axis of rotation at the anterior nasal spine), markings were placed 5° superior and inferior to Frankfort horizontal. These markings assisted in the alignment of the skull with the panoramic units' horizontal light guide, while maintaining the midsagittal plane parallel with the vertical light guide. Test exposures were made in each unit to establish values for kV and mA that provided images with sufficient density and contrast for future landmark identification.

The Orthophos DS operated with a CCD-sensor with an effective detector array of 138 x 5.9 mm^2 providing an individual pixel size of 45μ. To reduce file size, the pixel size was stored at 90μ. This provided a theoretical spatial resolution of 5.6lp/mm and a total image size of 3000 x 1540 pixels. The signals were acquired at a bit depth of 12 bit

(4096 shades of gray), however this was reduced to 8 bit (256 shades of gray) in the default preprocessing procedure.

4.2.6 Radiographic Distance Measurements

Radiographic images from the two conventional panoramic units (Unit 1 and Unit 2) were scanned at a resolution of 600dpi with the Epson Expression 1680 (Epson America, Long Beach, CA). Images from the three panoramic radiography units were digitized separately and each of the 125 images were digitized five times in random order using a custom designed software program (Crushersoft Software, Edmonton, Alberta). This program then generated the radiographic distances in the form of an excel spreadsheet.

4.2.7 Magnification Factor and Distortion Index

The magnification factor is the ratio of the radiographic distance to the actual distance. Comparison of the standard deviation of the true distance measurements with the standard deviation of the radiographic distance measurements revealed that the standard deviations were generally smaller for the true distance measurements. This allowed calculation of the magnification factor for each radiographic distance using the mean of the true distance measurements.

The distortion index is the ratio of the vertical magnification factor to the horizontal magnification factor. A distortion index with a value equal to one indicates that there is no distortion and the proportions of the object being imaged are depicted correctly. The following combinations of vertical and horizontal magnifications were

used to calculate the distortion indexes in various areas of the TMJ image: H1W1, H1W2, H1W3, H2W1, H2W2, H2W3, H3W1, H3W2, H3W3, HFWF.

4.2.8 Radiographic Shape Analysis

Radiographic images from the three panoramic units (Unit 1 and Unit 2) were digitized and mathematically reconstructed using a University of Alberta custom designed software program (Crushersoft Software, Edmonton, Alberta). The condylar outlines were truncated at a reference line that delineated the condyle from the ramus. Images from the three panoramic radiography units were digitized separately and each of the 125 images were digitized three times in random order. The software program then generated the average condylar shape for each image.[5]

To determine differences between two condylar shapes, one condylar shape was normalized mathematically relative to a second with respect to its size (area) and orientation. Shape comparisons were performed by superimposing the normalized condylar shapes on the reference line. The difference in shape was expressed as a percentage of the sum of dissimilar areas and was generated in the form of an excel spreadsheet. As shape area comparison was the only area-related quantity of interest, the units of area (the number of pixels or units of length squared) were not important, being that they were lost in the ratio calculations. To determine differences between the ideal head position and the four non-ideal head positions for each panoramic radiography unit, the average condylar shape from the five images at the ideal head position were compared to the corresponding average condylar shapes from each of the four non-ideal head positions ie. OP 100 ideal image 1 vs. OP 100 right image 1, OP 100 ideal image 2

vs. OP 100 right image 2. As a result, five shape comparisons out of a possible 15 combinations were completed for each non-ideal head position and for each panoramic radiography unit.

4.2.9 Error of Method

All skull modifications, skull positioning in the panoramic radiography units, and distance measurements (actual and radiographic) were performed by the principle investigator.

The total error for the distance and the shape difference measurements was a combination of the digitization error and the repeated head positioning error. For the distance measurements, the total error for each unit ranged 0.03mm to 0.60mm (OP 100), 0.02mm to 0.30mm (PM 2002 CC Proline), and 0.05mm to 0.45mm (Orthophos DS). For the shape difference measurements, the total error for each unit ranged from 0.5% to 1.0% (OP 100), 0.7% to 1.0% (PM 2002 CC Proline), and 0.8% to 2.3% (Orthophos DS). Other negligible errors could be derived from the mathematical procedure involved in reconstruction of the condylar outline.

4.2.10 Statistical Analysis

Repeated measures ANOVA (Bonferroni pairwise comparisons) was completed for each distortion index to detect differences between the ideal head position and the four non-ideal head positions. One sample t-tests were performed to determine statistical significance of the shape differences between ideal head position and each of the four non-ideal head positions. Condylar shape differences were compared to a theoretical

shape difference of zero. Any statistically significant deviation from zero suggested that the change in head positioning had a significant effect on the shape of the condyle. Significance levels less than 5% were considered to be statistically significant.

4.3 Results

Mean and standard deviation values of the distortion indexes for the ideal head position and the four non-ideal head positions (5° right, 5° left, 5° up, 5° down) are presented in Tables 4.1, 4.2 and 4.3. Repeated measures ANOVA (Bonferroni pairwise comparisons) comparing the ideal head position to each of the four non-ideal head positions are presented in Tables 4.4, 4.5, and 4.6.

The distortion indexes for the three panoramic radiography units ranged from 0.76 to 0.89 (OP 100), 0.95 to 1.06 (PM 2002 CC Proline), and 0.98 to 1.04 (Orthophos DS). The majority of distortion indexes (97%) for the OP 100 were statistically significantly different from the ideal head position, except anteclination. In general, distortion indexes decreased with rotation to the right and increased with rotation to the left and retroclination. Similarly, rotation to the right was the only non-ideal head position where the distortion indexes for the PM 2002 CC Proline were not statistically significantly different from the ideal head position. There was a generalized decrease in the distortion indexes with deviation from the ideal head position. For the Orthophos DS, the majority of distortion indexes (95%) were statistically significantly different from the ideal head position, except rotation to the left and retroclination. A trend towards a decrease in distortion indexes was also noted with this unit.

Differences between the average condylar shape at the ideal head position and each of the four non-ideal head positions, along with the mean and standard deviation values are presented in Tables 4.7, 4.8 and 4.9. One sample t-tests to determine the statistical significance of shape differences for the four non-ideal head positions are presented in Table 4.10. The results revealed that all three panoramic radiography units had statistically significant differences between the condylar shape at the ideal head position and the four non-ideal head positions. The Orthophos DS had the smallest shape differences ranging from 3.8% to 4.9%, while the PM 2002 CC Proline had the largest shape differences ranging from 8.6% to 12.3%.

4.4 Discussion

Magnification and distortion of a panoramic image are influenced by mandibular morphology and head position. In this study, mandibular morphology was kept constant by the utilization of one TMJ from a single skull. Therefore, the observed changes in the distortion of the lateral TMJ images from each panoramic radiography unit are due to variation in head position.

Simulation of common patient positioning errors during panoramic radiography was achieved by rotation of the skull in the horizontal and vertical planes. The decision to select a 5° vertical and horizontal head rotation was based on an attempt to be as clinically relevant as possible. Visualization of the degree to which the skull deviated from the ideal head position suggested that it would likely represent the upper limit of improper patient position by qualified personnel in clinical practice.

The results of this study revealed that the majority of the non-ideal head positions from all three panoramic radiography units had a statistically significant effect on the distortion of the lateral TMJ images. The differences in the distortion indexes between the ideal head position and the four non-ideal head positions were machine-dependent. The Orthophos DS demonstrated the greatest tolerance towards changes in head position with two of the four non-ideal head positions having no statistically significant differences. A companion study comparing the dimensional accuracy of the three panoramic radiography units at ideal head position demonstrated that that the OP 100 had the largest amount of distortion with distortion indexes as low as 0.78.[5] A distortion index with a value of less than one indicated that the horizontal magnification index was greater than the vertical magnification index. The distortion indexes for the OP 100 appeared to improve with rotation to the left and retroclintation, suggesting that the condyle was positioned closer to the central plane focal trough than at the ideal head position. The opposite effect occurred with rotation to the right. The PM 2002 CC Proline and the Orthophos DS behaved similarly in that the amount of distortion increased with deviation from the ideal head position.

All three panoramic radiography units had statistically significantly differences between the condylar shape at the ideal head position and the four non-ideal head positions. These differences were independent of the size and orientation of the condyle as depicted on the radiographic image. The observed differences for each of the head positions is related to the angulation of the x-ray beam relative to the long axis of the condyle. This relationship changed as the skull was rotated about the vertical and horizontal axis. The Orthophos DS demonstrated the greatest tolerance towards changes

in head position, while the PM 2002 CC Proline demonstrated the least tolerance. However, in a companion study that investigated condylar shape differences between lateral TMJ images from tomography and three panoramic radiography units at the ideal head position, the largest average difference in condylar shape was observed with the Orthophos DS, while smallest average difference was observed with the PM 2002 CC Proline.[5]

Although statistically significant differences in distortion indexes were found for the majority of the non-ideal head positions, many of these differences are very small and may not be clinically relevant. Perhaps distortion index differences of -0.01 to -0.03 for the PM 2002 CC Proline and the Orthophos DS are beyond the limits of perceptibility of the practitioner. A review of the current literature did not reveal any studies that investigated clinically significant tolerance limits for radiographic magnification or distortion that could be applied to the results of this study.

The results of this study can only be applied to the particular models of panoramic radiography units utilized. In addition, the use of a single skull does not allow for extrapolation of the results of this study to the population in general. However, the principles of magnification and distortion in panoramic radiography can be applied to all mandibular morphologies.

4.5 Conclusion

The following conclusions can be drawn from this study:

1. The majority of distortion indexes for the 4 non-ideal head positions were statistically significantly different from the ideal head position for the OP 100, PM 2002 CC

Proline and the Orthophos DS. The Orthophos DS demonstrated the greatest tolerance towards changes in head position. These differences were machine dependent.

2. Statistically significant differences were found between the condylar shape at the ideal head position and the four non-ideal head positions. The Orthophos DS demonstrated the greatest tolerance towards changes in head position, while the PM 2002 CC Proline demonstrated the least tolerance.
3. Further research needs to be conducted to determine clinically significant tolerance limits for radiographic magnification and distortion.
4. Lateral TMJ images from the PM 2002 CC Proline and the Orthophos DS may be suitable for the initial examination of the osseous structures of the TMJ. However, practitioners should be aware of the limitations of this technique and have an understanding of the potential effects of patient positioning errors on image distortion.

Table 4.1 OP 100: Mean and standard deviation values for the calculated distortion index

Distance	DISTORTION INDEX (5 HEAD POSITIONS)									
	Ideal		5 Right		5 Left		5 Up		5 Down	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
H1W1	0.81	0.01	0.78	0.02	0.84	0.02	0.83	0.02	0.81	0.03
H1W2	0.80	0.01	0.77	0.01	0.84	0.01	0.82	0.02	0.80	0.04
H1W3	0.79	0.01	0.77	0.01	0.84	0.01	0.82	0.02	0.79	0.03
H2W1	0.81	0.01	0.78	0.02	0.83	0.01	0.82	0.02	0.81	0.03
H2W2	0.80	0.01	0.77	0.01	0.83	0.01	0.82	0.02	0.80	0.04
H2W3	0.79	0.01	0.76	0.01	0.84	0.01	0.81	0.02	0.79	0.03
H3W1	0.80	0.01	0.77	0.02	0.83	0.01	0.82	0.02	0.80	0.03
H3W2	0.79	0.01	0.76	0.01	0.83	0.01	0.81	0.02	0.80	0.04
H3W3	0.78	0.01	0.76	0.01	0.83	0.01	0.80	0.02	0.78	0.03
HFWF	0.87	0.04	0.86	0.01	0.89	0.02	0.88	0.02	0.89	0.03

Distortion index = vertical magnification factor/horizontal magnification factor

A distortion index *greater* than 1.00 indicates that the vertical magnification is greater than the horizontal magnification

A distortion index *less* than 1.00 indicates that the horizontal magnification is greater than the vertical magnification

Table 4.2 PM 2002 CC Proline: Mean and standard deviation values for the calculated distortion index

Distance	DISTORTION INDEX (5 HEAD POSITIONS)									
	Ideal		5 Right		5 Left		5 Up		5 Down	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
H1W1	1.01	0.01	1.00	0.02	0.98	0.02	0.98	0.01	0.98	0.01
H1W2	0.99	0.01	0.98	0.02	0.97	0.01	0.97	0.01	0.97	0.01
H1W3	0.98	0.01	0.97	0.02	0.97	0.01	0.96	0.01	0.97	0.01
H2W1	1.00	0.01	1.00	0.02	0.98	0.01	0.98	0.01	0.98	0.01
H2W2	0.99	0.01	0.98	0.02	0.97	0.01	0.97	0.01	0.97	0.01
H2W3	0.98	0.01	0.97	0.01	0.97	0.01	0.96	0.01	0.96	0.01
H3W1	0.99	0.01	0.99	0.02	0.98	0.01	0.97	0.01	0.98	0.01
H3W2	0.98	0.01	0.97	0.02	0.97	0.01	0.97	0.01	0.96	0.01
H3W3	0.97	0.01	0.96	0.01	0.96	0.01	0.95	0.01	0.96	0.01
HFWF	1.06	0.01	1.06	0.02	1.03	0.01	1.03	0.02	1.03	0.01

Distortion index = vertical magnification factor/horizontal magnification factor

A distortion index *greater* than 1.00 indicates that the vertical magnification is greater than the horizontal magnification

A distortion index *less* than 1.00 indicates that the horizontal magnification is greater than the vertical magnification

Table 4.3 Orthophos DS: Mean and standard deviation values for the calculated distortion index

Distance	DISTORTION INDEX (5 HEAD POSITIONS)									
	Ideal		5 Right		5 Left		5 Up		5 Down	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
H1W1	1.01	0.02	0.99	0.01	1.01	0.02	0.99	0.03	0.99	0.01
H1W2	1.01	0.02	0.99	0.02	1.01	0.02	0.99	0.03	0.99	0.01
H1W3	1.03	0.02	1.00	0.01	1.04	0.02	1.01	0.03	1.01	0.01
H2W1	1.01	0.02	0.99	0.02	1.01	0.02	0.99	0.03	0.99	0.01
H2W2	1.01	0.03	0.99	0.02	1.01	0.02	0.99	0.03	0.99	0.01
H2W3	1.03	0.02	1.00	0.02	1.04	0.02	1.01	0.03	1.01	0.01
H3W1	1.00	0.02	0.98	0.01	1.01	0.02	0.98	0.02	0.98	0.01
H3W2	1.00	0.02	0.98	0.02	1.00	0.02	0.98	0.03	0.98	0.01
H3W3	1.02	0.02	0.99	0.02	1.03	0.02	1.00	0.02	1.00	0.01
HFWF	1.01	0.03	1.01	0.02	1.01	0.02	1.01	0.03	0.99	0.02

Distortion index = vertical magnification factor/horizontal magnification factor

A distortion index *greater* than 1.00 indicates that the vertical magnification is greater than the horizontal magnification

A distortion index *less* than 1.00 indicates that the horizontal magnification is greater than the vertical magnification

Table 4.4 OP 100: Repeated Measures ANOVA (Bonferroni pairwise comparisons) of distortion indexes between ideal head position and four non-ideal head positions*

Distance	Ideal vs. Right		Ideal vs. Left		Ideal vs. Up		Ideal vs. Down	
	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value
H1W1	-0.026	0.000*	0.027	0.000*	0.020	0.000*	0.001	1.000
H1W2	-0.030	0.000*	0.032	0.000*	0.019	0.002*	0.001	1.000
H1W3	-0.025	0.000*	0.051	0.000*	0.027	0.000*	0.002	1.000
H2W1	-0.026	0.000*	0.028	0.000*	0.016	0.000*	0.004	1.000
H2W2	-0.030	0.000*	0.032	0.000*	0.014	0.028*	0.002	1.000
H2W3	-0.025	0.000*	0.051	0.000*	0.023	0.000*	0.001	1.000
H3W1	-0.026	0.000*	0.030	0.000*	0.016	0.000*	0.003	1.000
H3W2	-0.030	0.000*	0.034	0.000*	0.015	0.037*	0.001	1.000
H3W3	-0.026	0.000*	0.053	0.000*	0.023	0.001*	0.001	1.000
HFWF	-0.011	0.040*	0.014	0.002*	0.006	1.000	0.017	0.157

Mean difference = non-ideal head position (5° right, 5° left, 5° up, 5° down) – ideal head position

* A P-value less than 0.050 is considered statistically significant

Table 4.5 **PM 2002 CC Proline: OP 100: Repeated Measures ANOVA (Bonferroni pairwise comparisons) of distortion indexes between ideal head position and four non-ideal head positions***

Distance	Ideal vs. Right		Ideal vs. Left		Ideal vs. Up		Ideal vs. Down	
	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value
H1W1	-0.002	1.000	-0.024	0.000*	-0.024	0.000*	-0.018	0.001*
H1W2	-0.009	0.533	-0.017	0.000*	-0.018	0.000*	-0.017	0.000*
H1W3	-0.007	0.712	-0.013	0.000*	-0.021	0.000*	-0.016	0.001*
H2W1	-0.002	1.000	-0.022	0.000*	-0.022	0.000*	-0.017	0.001*
H2W2	-0.008	0.359	-0.015	0.000*	-0.016	0.000*	-0.016	0.000*
H2W3	-0.007	0.412	-0.011	0.000*	-0.019	0.000*	-0.015	0.001*
H3W1	-0.002	1.000	-0.018	0.000*	-0.020	0.000*	-0.017	0.004*
H3W2	-0.008	0.446	-0.011	0.005*	-0.015	0.000*	-0.016	0.000*
H3W3	-0.007	0.538	-0.007	0.047*	-0.017	0.000*	-0.015	0.005*
HFWF	0.004	1.000	-0.027	0.000*	-0.029	0.000*	-0.026	0.000*

Mean difference = non-ideal head position (5° right, 5° left, 5° up, 5° down) – ideal head position
* A P-value less than 0.050 is considered statistically significant

Table 4.6 **Orthophos DS: Repeated measures ANOVA (Bonferroni pairwise comparisons) of distortion indexes between ideal head position and four non-ideal head positions***

Distance	Ideal vs. Right		Ideal vs. Left		Ideal vs. Up		Ideal vs. Down	
	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value
H1W1	-0.018	0.004*	0.003	1.000	-0.017	0.161	-0.017	0.000*
H1W2	-0.022	0.003*	0.002	1.000	-0.018	0.147	-0.024	0.000*
H1W3	-0.025	0.000*	0.007	1.000	-0.015	0.367	-0.024	0.000*
H2W1	-0.018	0.008*	0.003	1.000	-0.017	0.193	-0.016	0.000*
H2W2	-0.022	0.006*	0.002	1.000	-0.019	0.180	-0.022	0.000*
H2W3	-0.025	0.000*	0.007	1.000	-0.016	0.436	-0.022	0.000*
H3W1	-0.018	0.002*	0.004	1.000	-0.018	0.161	-0.015	0.000*
H3W2	-0.023	0.001*	0.003	1.000	-0.018	0.156	-0.022	0.000*
H3W3	-0.025	0.000*	0.008	1.000	-0.015	0.348	-0.022	0.000*
HFWF	-0.005	1.000	0.004	1.000	0.003	1.000	-0.017	0.022*

Mean difference = non-ideal head position (5° right, 5° left, 5° up, 5° down) – ideal head position
* A P-value less than 0.050 is considered statistically significant

Table 4.7 OP 100: Shape differences between the ideal head position and each of the four non-ideal head positions (%)

Image Number	Ideal vs Right	Ideal vs Left	Ideal vs Up	Ideal vs Down
1	3.0	18.2	6.0	7.9
2	8.5	7.4	7.7	6.1
3	5.7	4.7	6.5	4.7
4	6.7	6.6	5.0	5.4
5	8.5	6.8	5.2	5.5
Mean ± S.D.	6.5 ± 2.3	8.7 ± 5.4	6.1 ± 1.1	5.9 ± 1.2

Table 4.8 PM 2002 CC Proline: Shape differences between the ideal head position and each of the four non-ideal head positions (%)

Image Number	Ideal vs Right	Ideal vs Left	Ideal vs Up	Ideal vs Down
1	11.8	19.5	8.6	13.1
2	10.0	13.3	9.1	13.9
3	14.1	9.9	7.2	11.3
4	12.2	8.6	8.8	11.5
5	13.7	8.6	9.4	11.9
Mean ± S.D.	12.3 ± 1.6	12.0 ± 4.6	8.6 ± 0.9	12.3 ±1.1

Table 4.9 Orthophos DS: Shape differences between the ideal head position and each of the four non-ideal head positions (%)

Image Number	Ideal vs Right	Ideal vs Left	Ideal vs Up	Ideal vs Down
1	6.1	5.1	3.3	4.0
2	3.0	2.9	3.4	4.0
3	4.4	4.5	2.7	5.8
4	6.1	4.6	6.5	2.8
5	5.1	2.2	2.9	4.6
Mean ± S.D.	4.9 ± 1.3	3.8 ± 1.2	3.9 ± 1.6	4.2 ± 1.1

Table 4.10 One sample t-test comparisons of shape differences between the ideal head position and four non-ideal head positions*

Ideal vs. Non-ideal Head Position	OP 100		PM 2002 CC Proline		Orthophos DS	
	t-Value	P-value	t-Value	P-value	t-Value	P-value
Right	6.3	0.003*	17.1	0.000*	8.6	0.001*
Left	3.6	0.023*	5.8	0.004*	7.0	0.002*
Up	12.2	0.000*	22.4	0.000*	5.6	0.005*
Down	10.8	0.000*	24.6	0.000*	8.7	0.001*

Test value = 0% (theoretical shape difference)

* A P-value of less than 0.050 is considered statistically significant

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Chapter Five

Discussion
And
Recommendations

5.1 General Discussion

The temporomandibular joint (TMJ) is technically one of the most difficult areas of the body to image successfully because of multiple adjacent osseous structures.[1, 2] Selecting an appropriate imaging modality requires knowledge of the type of diagnostic information required. When evaluating the osseous structures of the TMJ, panoramic radiography, conventional tomography and computed tomography provide information with varying degrees of detail. Because of the cost and the relatively high risk of radiation exposure associated with computed tomography, the American Academy of Oral and Maxillofacial Radiology has recommended the use of conventional tomography except when evaluating foreign body giant cell reactions, ankylosis and complex facial fractures.[3] The main advantage of conventional tomography over panoramic radiography is that it blurs out shadows of superimposed anatomical structures which obscure information pertaining to the TMJ. Complex motion tomography is preferred over linear tomography because it provides more effective blurring of structures outside the focal plane.[4] Individualized positioning of the x-ray beam relative to the anatomy of the condyle in the axially corrected technique is considered by many to provide the most reliable and accurate information about the osseous structures of the TMJ. [1, 5, 6, 7]

Panoramic radiography has been advocated by many authors as a good imaging modality for examination of the TMJ, since it also provides information about the maxillary and mandibular arches and their supporting structures. [3, 5-8] Panoramic radiography units are available in many dental practices because it is a cost effective technique that has a reasonably low patient radiation dose. Based on the information obtained from the clinical examination and the panoramic radiograph, the need for further

radiographic TMJ imaging can be determined by the practitioner. In view of the high cost of using modern imaging modalities such as MRI and CT, such an approach to patient management is desirable.

As with any radiographic technique, there are several limitations associated with panoramic radiography. Limitations such as image magnification and distortion have been described extensively in the literature.[9-20] Magnification is an inherent part of panoramic radiography and is dependent upon the position of an object between the x-ray source and the film. In the central plane of the focal trough, magnification is identical in the horizontal and vertical dimensions. Distortion occurs when the object is displaced away from the central plane of the focal trough. The focal trough is designed to match a generic mandibular form. Different manufacturers have created subtle differences in the design of the focal trough, some focusing more on the TMJ than others. To obtain a panoramic image with minimal distortion, it is imperative that the patient be positioned such that the dental arches are located precisely in the center of the focal trough. Even if the patient is ideally positioned, distortion can occur as a result of the nonorthogonal alignment of the x-ray beam with anatomy of the TMJ.[21, 22]

In recent years, there have been many technological advances in panoramic radiography including multiple imaging programs that focus on specific anatomic sites. Panoramic radiography units such as the OP 100, the PM 2002 CC Proline, and the Orthophos DS have specialized programs that provide lateral and frontal views of the TMJ. These programs provide arbitrary corrections for horizontal condylar axis angulation based on population norms, which may potentially minimize the amount of distortion seen on conventional panoramic radiographs due to non-optimal imaging

geometry. The goal of using any new imaging technique is to accurately represent the "anatomic truth" of the structure being imaged. Although the diagnostic accuracy of the lateral TMJ images from panoramic radiography has been investigated to some extent, the anatomic accuracy of these images has yet to be determined. [23, 24]

The investigation of the anatomic accuracy of lateral TMJ images from panoramic radiography was divided into three separate studies. The purpose of the first study was to compare the true dimensions of the TMJ of a dry human skull to the radiographic dimensions on lateral TMJ radiographs from axially corrected tomography and three panoramic radiography units. The purpose of the second study was to compare the radiographic shape of the condyle between lateral TMJ images from axially corrected tomography and three panoramic radiography units. The purpose of the third study was to evaluate the effect of varying horizontal and vertical head rotation of a dry human skull on the radiographic dimensions of the TMJ and the shape of the condyle from each of three panoramic radiography units and to compare these finding to the ideal head position.

The true dimensions of the TMJ were calculated using a Coordinate Measuring Machine (HGC Model, Starrett Corporation, U.S.A). The CMM utilizes frictionless air bearings and a touch trigger probe to record the X, Y, and Z coordinates with a reported linear accuracy of 0.0038mm.[25] The manually adjustable probe head, which was 1mm in diameter allowed access to the varying locations of markers on the head of the condyle and the mandibular fossa. Each series of 10 markers was digitized in random order five separate times. Because the markers used in this study were spheres, the linear distances were calculated between the center points of the spheres. Reproducibility of the linear

distances varied from 0.004mm to 0.122mm. An image of the digitized markers generated by the CMM software program verified that the markers on the surfaces of both the condyle and fossa were generally all placed along the same plane. Axially corrected tomographs were taken with the CommCAT multidirectional tomography unit (Imaging Sciences International Inc., Roebling, NJ). The horizontal condylar axis angulation was calculated using a submentovertex film according to the manufacturer's guidelines. For the right TMJ, the angulation was within the limits of normal anatomic variation, which ranges from 11 to 35 degrees.[26] A slice thickness of 6mm was chosen to ensure that the 10 markers would be located within the tomographic plane.

For each panoramic radiography unit, the skull was positioned according to the manufacturers' guidelines for TMJ imaging. The guidelines for the three units were similar in that the skull was centered using the midsagittal plane, while Frankfurt horizontal was maintained parallel to the floor. References lines were placed on the frontal and lateral aspects of the skull representing the midsagittal plane and Frankfort horizontal respectively. These reference lines assisted in the precise alignment of the skull with the unit's horizontal and vertical positioning light guides. Therefore, it could be argued that skull positioning was likely more accurate than patient positioning would be in a clinical setting.

Each panoramic radiography unit had additional positioning guides that were unique to the manufacturer. For the OP 100, a nose support was used to stabilize the skull and a TMJ pointer was adjusted anteroposteriorly until it was aligned with the external auditory meatus. For the PM 2002 CC Proline, the temple and chin supports were used to stabilize the skull, while the focal trough light was used to position the skull testing

device anteroposteriorly. The focal trough light was adjusted to fall between the lateral incisor and the canine. The distance between the focal trough light and the center of the external auditory meatus was then measured. Using a positioning guide table provided by the manufacturer, this distance was used to determine how much the skull testing device would have to be moved anteroposteriorly to be correctly positioned. For the Orthophos DS, the ear fixations of the head positioner were inserted into the external auditory meatus to guide the positioning of the skull, while the contact spacer was used to stabilize and support the forehead. Of the three panoramic radiography units, the PM 2002 CC Proline had the most complicated patient positioning technique. It is likely that the types of patient positioning errors may vary between panoramic radiography units because of the various positioning guides provided. However, for consistency in the third study, the skull was rotated about the same horizontal and vertical axis for each panoramic radiography unit.

Exposure settings on the three panoramic radiography units could not be standardized. All three panoramic radiography units featured fully customized kV and mA settings allowing exposure without beam attenuation. The tomography unit required beam attenuation in the form of two lead sheets. Test exposures were made in each unit to establish values for kV and mA that provided images with optimum quality. It is unlikely that the differences in image density and contrast affected the reproducibility of landmark identification for the distance measurements.

The image layers of the panoramic radiography units for the lateral TMJ programs are wider than the tomographic image layer. A wider image layer produces less blurring of the adjacent structures. Ludlow et al found that the residual blur is better defined in

panoramic images and may be more easily confused with actual joint anatomy.[24] In this study, utilizing the center of the radiopaque stainless steel balls for digitization reduced the subjectivity of radiographic landmark identification. However, it is possible that the measurement error associated with digitization of the markers and the radiographic outline of the condyle may be affected by the sharpness of the TMJ image.

The results of the first study revealed that there was a statistically significant amount of dimensional distortion of the condyle and mandibular fossa on lateral TMJ images from the tomography unit and the three panoramic radiography units. Of the four units, the lateral TMJ images from the OP 100 had the largest amount of distortion, followed by the PM 2002 CC Proline, the Orthophos DS, and the CommCAT. The magnitude of these differences were very small with the exception of the OP 100, which had distortion index differences that were statistically significantly different from the CommCAT, the PM 2002 CC Proline, and the Orthophos DS. In a clinical setting, these differences may be beyond the limits of perceptibility of the practitioner. Therefore, it is unlikely that these statistically significant findings are clinically significant. A review of the current literature did not reveal any studies that investigated clinically significant tolerance limits for radiographic magnification or distortion that could be applied to the results of this study.

In the second study, statistically significant differences in the shape of the condyle were found between the lateral TMJ images from the tomography unit and each of the three panoramic radiography units. The lateral TMJ images from the PM 2002 CC Proline demonstrated the smallest shape difference, followed by the OP 100 and the Orthophos DS. The observed differences in condylar shape between the tomography unit

and the three panoramic radiography units can be attributed to differences in the size of the image layers, the position of the condyle within the focal trough, and the direction of the x-ray beam relative to the horizontal long axis of the condyle. Although the lateral TMJ programs are designed to provide arbitrary corrections for horizontal condylar axis angulation, the direction of the x-ray beam relative to the TMJ may vary between the panoramic radiography units. As a result, the lateral TMJ images from the panoramic radiography units are most likely oblique views of varying degrees. If condylar shape is to be compared longitudinally, it is imperative that the same panoramic radiography unit be used. Despite the inherent differences in the imaging geometry between tomography and panoramic radiography units, a subjective assessment of the lateral TMJ images revealed that the condylar shape from the PM 2002 CC Proline was remarkably similar to the condylar shape from the CommCAT. This suggests that the direction of the x-ray beam closely approximated the horizontal condylar axis angulation of the skull testing device.

The third study examined the effects of four non-ideal head position (5° right, 5° left, 5° up, 5° down) on the dimensions of the TMJ and condylar shape and compared these results to the ideal head position. Variation in head position was found to have a statistically significant effect on the distortion indexes and condylar shape of the lateral TMJ images from all three panoramic radiography units. Again, the differences in the distortion indexes between the ideal head position and the four non-ideal head positions were very small. Similar to the results of the first study, it is unlikely that these differences are clinically significant. The Orthophos DS demonstrated the smallest condylar shape differences between the ideal head position and the four non-ideal head

positions. It is interesting to note that while the Orthophos DS demonstrated the greatest tolerance towards changes in head positioning, in the second study this unit had the greatest difference in condylar shape compared to axially corrected tomography. Conversely, the PM 2002 CC Proline demonstrated the least tolerance towards changes in head position and had the smallest difference in condylar shape compared to tomography.

The results of the three studies combined suggested that the PM 2002 CC Proline provided the most anatomically accurate image of the TMJ at the ideal head position. However, it is important to note that the results of this study can only be applied to the skull testing device and the particular models of panoramic radiography units utilized. With any panoramic radiography unit, practitioners should have an understanding of the potential for image distortion, particularly since the degree and type of distortion cannot be defined or quantified in a clinical setting. Therefore, if the findings from the clinical examination and the lateral TMJ panoramic radiographs suggest the potential for disease, further radiographic imaging that provides detailed visualization of the osseous structures should be requested.

5.2 Future Recommendations

The panoramic radiography units used in this investigation had specialized programs that provided both lateral and frontal views of the TMJ. In axially corrected tomography, the frontal (coronal) view has been recommended to view the laterosuperior and the mediosuperior surfaces of the condyle.[5] It would seem reasonable that the frontal TMJ images from panoramic radiography may also provide additional diagnostic

information. Since the focus of this investigation was limited to lateral TMJ imaging, a future study could evaluate the anatomic accuracy of frontal TMJ images.

In this investigation, radiographic imaging was completed on one TMJ, thus only one type of condylar morphology was examined. It is well known that a large amount of anatomic variation exists in the general population and that changes in condylar morphology can affect panoramic image generation. The focus of this study could be expanded to include skulls with varying condylar morphologies, particularly those with a wide range of horizontal condylar axis angulations. The results from the various skulls can be compared to determine the effect of horizontal condylar axis angulation on radiographic image of the TMJ.

The third study investigated the effects of vertical and horizontal head rotation on the radiographic image of the right TMJ. However, other common patient positioning errors such as transverse bodily shift, anteroposterior bodily shift, and lateral tilt could also be investigated with the same skull testing device. Furthermore, horizontal head rotation and lateral tilt have the potential to produce varying effects on both TMJs, particularly if the condyles are displaced in different directions relative to the focal trough. Ruf and Pancherz found that lateral tilt of the skull influenced the symmetry of the two condyles in conventional panoramic radiography.[22] As a result, this investigation could be expanded to include the effects of positioning errors on both TMJs.

Although lateral TMJ images from panoramic radiography were compared to axially corrected tomography in the first study, it would be valuable to compare conventional panoramic radiographs and the specialized TMJ radiographs from each panoramic radiography unit. Such a comparison may determine if the imaging geometry

of the specialized TMJ programs provides a more accurate and reliable image than conventional panoramic radiographs.

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Appendix A

Test Device Design

Figure A.1 Skull (frontal view)

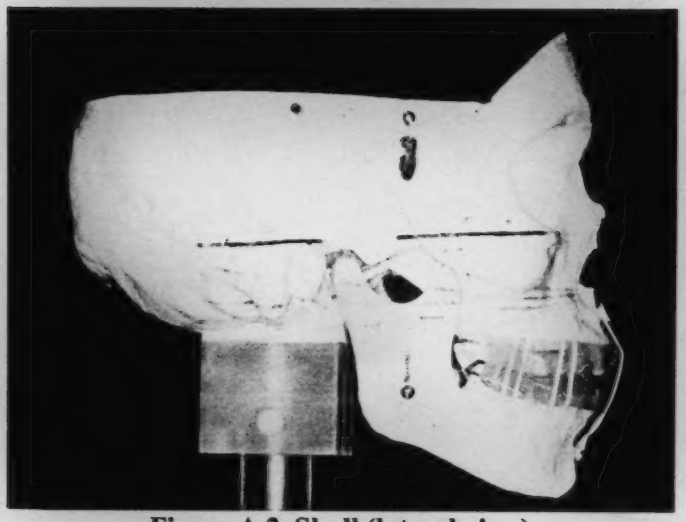

Figure A.2 Skull (lateral view)

Appendix B

Skull Holder for Radiographic Imaging

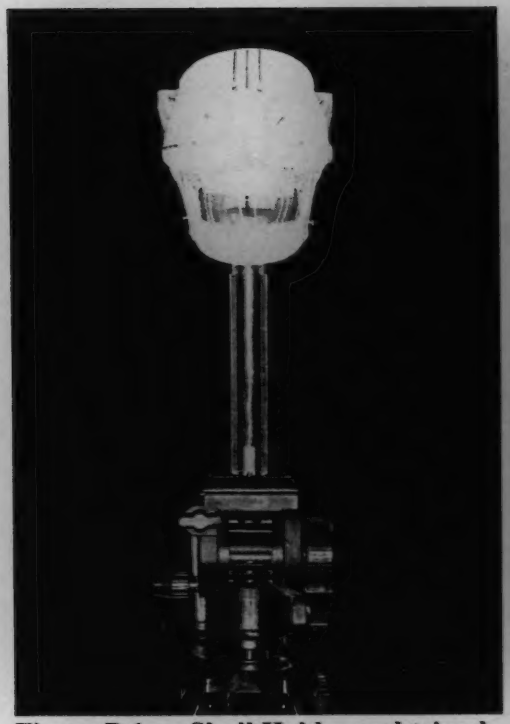

Figure B.1 Skull Holder and tripod (frontal view)

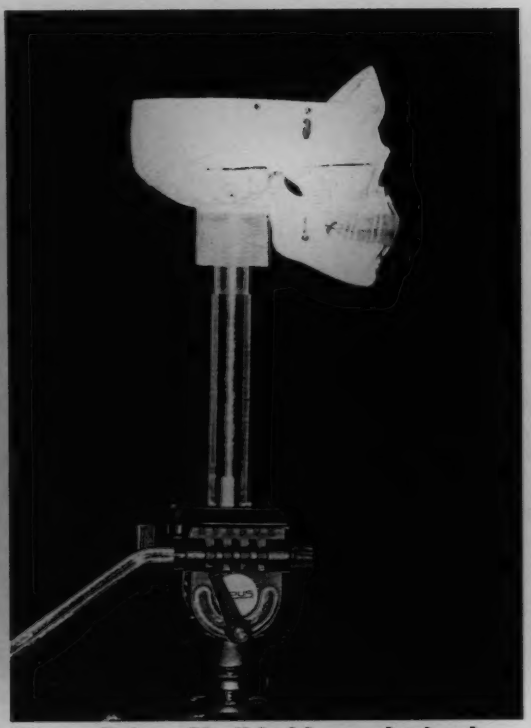

Figure B.2 Skull holder and tripod (lateral view)